The geomorphology of coarse clastic surfaces in arid environments

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Nicholas John Rosser

This thesis is submitted in accordance with the regulations for the degree of Doctor of Philosophy in the University of Durham, Department of Geography, 2002.

Declaration

I confirm that no part of the material presented in this thesis has previously been submitted by me or any other person for a degree in this or any other university. In all cases, where it is relevant, material from the work of others has been acknowledged.

Signed: NJ Rosser

Date: April 2003

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Abstract

This study explores the linkages between slope form and slope process in arid environments. In doing so, questions of the development of slopes in arid environments are examined. The age of many arid environment surfaces, combined with the sporadic nature of formative events, means that long-term surface and slope development remains an elusive question in geomorphology. Deserts have inspired many of the most enduring theories of landscape evolution and continue to provide a test-bed for new and emerging ideas in geomorphology. The clast-mantled surface of the northeast Jordan Badia presents an ideal opportunity to study the links between surface character and slope processes in arid environments. The northeast Badia also provides an opportunity to explore theories of slope development and the behaviour of earth surface systems.

The nature of the clast covered ground surface has been assessed using a new digital aerial photography and image analysis technique. A field study of surface processes has been used to explore links between surface form and slope process. Additionally, a computer based simulation of long-term modification of the spatial distribution of surface clast has been undertaken. Given the subtle variation in earth surface form between disparate locations, a new semi-quantitative method of locating sample sites has been developed. The characterization of surface form has identified statistically significant relationships between ground surface character and two-dimensional slope form. Systematic variations in ground surface configuration, both within and between basalt flows, are found to be indicative of the action of slope processes.

The first study of ground surface hydrology in the northeastern Badia has been undertaken. The results from a series of rain-storm simulation experiments show subtle but significant links between the action of surface processes and variations in ground surface form. The controls on surface process are diverse and vary in significance with position in the landscape. A combination of ground surface characterization and process studies has identified several interesting geomorphological phenomena The surfaces exhibit systematic variations in structure and organization. Homeostatic links between form and process are clearly apparent, which suggests that surface form influences and is influenced by process action via a process of positive feedbacks.

Given the sporadic and infrequent recurrence of formative events in arid environments, a modelling approach has been developed to understand the long-term, spatial dynamics of the ground surface. The model has been used to simulate structure in the surface clast arrangement and the sensitivity of surface organization to physically constrained variations in model parameters. The model also allows the surfaces to be considered as self-organizing earth surface systems. The model results provide new insights into the process-form linkages in operation on clast-mantled arid surfaces. The model results provide new ways of examining and understanding the dynamics of clast mantled arid surfaces and have implications for the application of self-organization in geomorphology.

Acknowledgements

The research in this thesis has only been made possible by the help and guidance which I have received from numerous sources over the last three years. First of all I would like to thank my Mum and Dad for providing constant support throughout my various geographical exploits. Second, I would like to thank my supervisors, Professor Bob Allison and Dr David Higgitt. Bob has been an effervescent source of enthusiasm and ideas throughout my studies. Dave has been instrumental, inspiring many of the ideas and approaches developed in this thesis. I would particularly like to thank Dave for being sympathetic when I dropped his digital camera from the kite, 100 m above the River Wear, and to Bob for providing a replacement!

The fieldwork for this thesis was based at Safawi, Jordan. This was possible only through the kind assistance of the Jordan Badia Research Development Programme (JBRDP). The continuing support of H.R.H. Prince Hassan bin Talal, H.H. Sharifa Zein bint Nasser, programme director Mohammed Shahbaz, Dr Salim Al-Oun and Dr Roderic Dutton, was kindly appreciated. For the majority of my fieldwork, my sole companions in the desert were the drivers of the JBDRP. Although we never had enough common language for me to explain why I was doing what I was doing, nonetheless without their immense knowledge of the northeast Badia this work would have been significantly more challenging. Of the drivers R'wayed Abu Sammi and Abu Abdullah Sliman deserve particular thanks, but also Rhalib, Mohammed Fal'hor, Abu Abdullah, Abu Rasha, Allah, Fa'lha Abu Rasha and Abdullah, were all fantastic. In addition, the staff of the JBRDP in Safawi: Rida, Ouda, Shaheen, Salah, Saad, Ismael Abu Rashed, Moufaq, Nadhal, Nadhal, Ali, Abu Mohammed, Mohammed Striman, Majidt, Khalid, Khalid and Mohammed made my various periods of fieldwork in Jordan an enjoyable and unforgettable experience. In addition, the staff of the JBRDP in Amman were invaluable in making things happen even when they, under normal conditions, perhaps should not. In particular I would like to thank Salah and Achmed for getting me, and the rainfall simulator, onto a plane that had already departed from Amman! I apologise for the spelling of everyone's name and inevitably missing some people out. Everyone's humour and support was greatly appreciated!

In Amman, the Centre for British Research in the Levant provided a welcome home from home, in addition to the loan of the Monopod camera boom and field equipment. Although not used to geomorphologists the staff, Dr Bill Finlayson, Sam, Charlie, Mohammed and Nadja, were incredibly supportive and helpful throughout my fieldwork.

Valuable assistance in the field was greatly appreciated. I would particularly like to thank Cate Noble for keeping my feet on the ground during the kite aerial photography, Dr Alex Wasse for his enthusiasm for desert expeditions, Ann Furr for providing a realistic view of life in the Badia, in addition to assistance in the field from James Grove, Tanya Mills, Simon Nelis and my brother Jonathan and now sister, Joh.

In Durham the staff and students of the Department of Geography have been a constant source of help and support. I am indebted to the Department of Geography for providing my studentship over the past three years. In the laboratories, Derek Coates, Frank Davies, Ian Dennison, Andrew Hudspeth, Eddie Million, Brain Priestley and Neil Tunstall have all been excellent. The staff of the department office, in particular Derek Hudspeth and Christine Bones have been invaluable in helping to arrange fieldwork in Jordan. I have benefited greatly from working and living in a vibrant postgraduate community. A particular mention goes to Andy Mills, Sarah Hamilton, Kathrin Blaufuss, Vicky Holliday and John Thompson, in addition to Katherine Arrell, Helen Dunsford, Joe Holden, Richard Johnson, Kay MacManus, Damien Laidler, Laura Park and Matt Wright.

Many elements of this thesis would not have been possible without the expertise of several people. In particular I would like to thank Dr Tom Sherratt, now of the Department of Biology, Carleton University, Ottawa, for his generous help and time with the code for the cellular automata model. Dr Nick Cox has, as ever, been a constant source of guidance, enthusiasm and wit on statistical techniques throughout my time at Durham. Also, I would like to thank Dr Louise Bull, Professor Tim Burt, Dr Ian Evans and Dr Jeff Warburton for their ideas and advice.

I have had the opportunity to discuss my research with many people outside of Durham. In the field, discussions with Professor Stephen Wells, of the DRI, Nevada, were a great inspiration. Closer to home, the opportunity to discuss my work with Professor Anthony Parsons and Professor Jean Poesen were also greatly appreciated. Comments after the presentation of this research at the IAG, Tokyo, 2001, provided valuable ideas for the completion of this thesis.

List of Contents

List of Tables

Chapter 2: The physical environment of the northeast Badia

Chapter 3: Site selection, description and sampling

Chapter 4: The characteristics of ground surface form

Chapter 5: Hydrological processes

Chapter 6: Modelling the development of coarse clastic surfaces in arid environments

List of Figures

Chapter 2: The physical environment of the northeast Badia

Chapter 3: Site selection, description and sampling

Chapter 4: The characteristics of ground surface form

Chapter 5: Hydrological processes

List of Plates

Chapter 2: The physical environment of the northeast Badia

Chapter 3: Site selection, description and sampling

Chapter 4: The characteristics of ground surface form

Notation

Symbols are defined where they are introduced. The corresponding SI units are the kilogram (kg), the metre (m), the litre (l) and the second (s). Some of the more commonly used symbols are the following:

Field site locations and names

Site name	Plot position on slope profile	Site code
Concave (CC)	Top	CCT
	Middle	CCM
	Bottom	CCB
Convex (CV)	Top	CVT
	Middle	CVM
	Bottom	CVB
Straight (ST)	Top	STT
	Middle	STM
	Bottom	STB
Swayed, site 1 (SW1)	Top	SW1T
	Upper	SW1U
	Middle	SW1M
	Lower	SW1L
	Bottom	SW1B
Swayed, site 2 (SW2)	Top	SW2T
	Upper	SW2U
	Middle	SW2M
	Lower	SW2L
	Bottom	SW2B
Qa'a al Buqei'wiya, site 1 (GW1)	Top	GW1T
	Upper	GW1U
	Middle	GW1M
	Lower	GW1L
	Bottom	GW1B
Qa'a al Buqei'wiya, site 2 (GW2)	Top	GW2T
	Upper	GW2U
	Middle	GW2M
	Lower	GW2L
	Bottom	GW2B

Chapter 4 Notation - Surface characterization

Variable	Type	Description
Gcp	Ground cover (derived from image analysis plot)	Percentage clast ground cover (%)
EdgeTot		Total edge length of all clasts (m)
Cv_b		Coefficient of variation
b		Intermediate axis (m)
ken.par	Slope variables	Kennedy parameter
UpslpAngle		Mean angle of slope 10 m above plot (degrees)
PltAngle		Plot angle (degrees)
PltDist		Distance of plot from slope crest (m)
Curv		Slope curvature (angle of slope 10m above plot minus angle of slope 10m below plot)
T_{vert}	Spatial analysis variables	Standard deviation of number of vertices of Theissen polygon network
R(l)		Nearest neighbour statistic
F_{box}		Box fractal dimension of exposed sediment area
VolwMb	Weighted means	Volume weighted mean intermediate axis (m)
AreawMb		Surface area weighted mean intermediate axis (m)
EdgewMb		Edge length weighted mean intermediate axis (m)
Gcp_{plot}	Plot statistics (derived from rainfall simulation plot area)	Percentage clast ground cover (%)
$EdgeTot_{plot}$		Total clast edge length (m)
B_{plot}		Mean intermediate axis (m)
Time	Misc.	Time into experiment (s)
ucam		Uncorrected arithmetic mean intermediate axis
ß		Multiple regression beta statistic
		Significance level
		Standard deviation

Chapter 5 Notation - Surface hydrology

Variable	Type	Description
f	Hortonian infiltration	Infiltration capacity (mm h^{-1})
f_c		Final infiltration rate (mm h^{-1})
f_o		Initial infiltration rate (mm h^{-1})
e		Exponential coefficient
k		Constant
t		Time (s)
R_{mean}	Runoff variables	Mean run off (mm h^{-1})
R_{max}		Maximum runoff recorded (mm h^{-1})
R_{tot}		Total runoff recorded (mm h^{-1})
S_{mean}	Sediment variables	Mean sediment yield (g h^{-1})
S_{max}		Maximum sediment yield recorded (g h^{-1})
S_{tot}		Total sediment delivered (g)
T_{start}	Timings	Time to start of runoff (s)
T_{max}		Time to maximum runoff (s)

Chapter 6 Notation - Modelling

Variable	Description
Matsize	Width and length of the cellular automata array
Totcl	Total number of clasts which defines cover percentage when combined with Matsize
small rocks	Defines clast size sorting, and number of large clasts when combined with Totcl
medium rocks	
ITmax	Number of iteration steps
Sangle	Angle of slope
p(small)	Probability of clast moving
p(medium)	
p(large)	
Diagonal friction (fdiag)	Friction between diagonal cells, upslope
Double diagonal friction (Dfddiag)	Friction between a cell and two diagonal upslope occupied cells
Lateral friction (flat)	Friction across slope between two cells
Org	Measures of model behaviour, defined in section 6.5.2
Lock	
Expapp	Asymptotic approach to equilibrium model
k-Lock	Rate of change in Expapp for Lock
y1-Lock	Estimated initial value of Lock in Expapp
Y2-Lock	Estimated final value of Lock in Expapp
k-Org	Rate of change in Expapp for Org
y1-Org	Estimated initial value of Org in Expapp
y2-Org	Estimated final value of Org in Expapp
Cv_b	Coefficient of variation of clast size
N, S, E, W, NE, NW, SE and SW	Relative cell positions
RMSE	Root mean squared error

List of appendices

A CD – ROM accompanies this thesis containing the appendices. The appendices are constructed in web-page format and are designed to be viewed in a standard web browser. The CD contains two sections:

1. Raw 12 m altitude images, used in Chapter 4
2. Cellular automata clast surface model, developed in Chapter 6

The pages contain instructions on how to view the images and run the cellular model. To view the appendices double-click on the Title.html icon in the Appendices folder and follow the instructions. Click the clast to return to the contents page.

Chapter 1: Introduction

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This thesis is concerned with form, process and the dynamics of evolution of rocky deserts. Rocky deserts present an intriguing geomorphological situation, combining the complexity of rock mantled surfaces with the intricacy of desert pavements and the dynamics of an actively developing drainage system. Our understanding of desert evolution suffers due to the sporadic nature of formative events and the slow rates of geomorphic change in arid environments. Landscape evolution continues to pose a series of elusive problems in geomorphology. The relationship between desert surface configuration and slope process activity is poorly understood and often hindered by a deficiency of accurate field data. The surfaces of the northeast Jordanian Badia Desert present an ideal opportunity to explore a dynamic, complex and intriguing arid geomorphological setting. The desert surfaces are largely undisturbed, presenting surface configurations which appear to be the result of a long sustained period of process action. Subtle links exist between both slope form, the character of the surface rocks and their configuration, geology and geomorphological context. Linkages are complex, with evidence of intricate feedbacks and dependencies between form and process. The results of this thesis, which explores these links, can be used to explore theories of slope development and apply these to the behaviour of earth surface systems in arid environments.

The purpose of this research is to develop a comprehensive understanding of the geomorphology of the desert landscape of the north eastern Badia. No previous study has attempted to combine a detailed understanding of the spatial variation in surface character with an assessment of the equally diverse influence of surface process action. A homeostatic link whereby surface form acts to alter process action and conversely, the action of processes acts to alter surface form, is suggested below. Peculiar surface features such as a notable level of spatial organization in the distribution of surface clasts manifested in clear surface patterns, have not previously been studied or documented. Previous work has identified the presence of systematic variations in surface character and linked to slope morphology and geology. This work has as yet failed to explain or link this variation to formative processes responsible for the modification of the slope surface character. This study develops a series of highly innovative techniques which precisely assess the variations in character of the desert surfaces. This is combined by a detailed and extensive study of surface hydrology as the principal mechanism of surface modification. When combined with a cellular modelling approach the results of this study have numerous implications for our understanding of earth surface systems and desert geomorphology.

1.1 Aims and Objectives

This study has a series of primary research aims:

i. examine the variations in ground surface character and configuration of arid coarse clastic surfaces;

ii. examine the variation in slope hydrology and process action on arid coarse clastic surfaces;

iii. explore the linkages between ground surface character, slope profile form and surface process action;

iv. use a detailed study of slope form and process as a basis for understanding the temporal development of clast surface organization;

v. apply the results of a model of surface dynamics, to aid the understanding of surface and landscape development.

To fulfil the aims of this thesis, a series of specific objectives were developed;

i. design an appropriate research framework within which the variation of surface form and process action can be examined;

ii. develop a method of surface characterization which derives surface measures which are applicable to both the action of slope processes and surface dynamics;

iii. design a suitable method of quantifying spatial variations in surface hydrology and the influence of ground surface character on slope process;

iv. develop a stochastic model which simulates the spatial organization and modification of surfaces, as dictated by the spatial variation in surface character identified in the field.

1.2 Background and justification of thesis

The study of desert slope processes and slope evolution has been restricted by a deficiency of accurate data with which to constrain models of landscape evolution (Nash, 2000). The long-term interaction between process and materials on rocky desert surfaces is poorly understood (Abrahams, *et al.*, 1994), possibly due to the difficulty of access in such hostile environments. It is argued that an understanding of many, if not the majority of geomorphological systems in deserts, must begin with an awareness of slope processes (Abrahams *et al.*, 1994). Desert surfaces are commonly regarded as highly sensitive and responsive geomorphic systems from which valuable indicators of geomorphological activity can be derived (Haff, 2001). The sensitivity of desert slope surfaces to disturbance and the interaction between form and process are of paramount importance to understanding a desert landscape, no where less than in the north eastern Badia.

Desert slopes are commonly mantled with a coarse layer of debris or rock fragments that is either weathered out from the underlying geology, or fallen from a superincumbent rock face (Abrahams *et al.*, 1994). The form of coarse clastic surfaces is diverse and the processes acting upon them equally complex. Studies have addressed various aspects of the geomorphology of coarse clast mantled slopes in arid environments (Abrahams and Parsons, 1992; Poesen and Lavee, 1994; Allison and Higgitt, 1998). The critical geomorphological distinction in this study is the absolute size of surface clasts and the nature of the underlying sediments. The surface clasts are massive relative to the size of the grains of the underlying sediments, distinguishing them from rock-fragment mantled surfaces. The second major distinction is the environment within which the surfaces are found. The climate is arid, with sporadic and infrequent high magnitude formative events, which have been suggested to hold a significant and unique influence over surface form and modification (Dorn, 1994).

Geomorphological research on coarse clastic surfaces is largely based on three separate themes: surface characterization (Dunkerley, 1995; Vincent and Sadah, 1995); the study of slope hydrology and hydraulics (Parsons and Abrahams, 1994); and the study of whole slope evolution (Friend *et al.*, 2001). The integration of these themes in the literature is rarely attempted and is often only tentative. Only a few authors have attempted to understand the relationship between two-dimensional slope form and ground surface variation or tried to draw together studies of surface character, process action and two-dimensional slope form development (Brown and Dunkerley, 1996; Allison and Higgitt, 1998). An overriding consideration which has emerged from previous work is the complexity and diversity of controls on coarse clastic surface geomorphology. The way in which the surface is characterized must be appropriate to the objective of the study, a notion termed *adequacy* by Dunkerley (1994). A holistic understanding of the slope surface geomorphology in the northeastern Badia is beyond the scope of this thesis, but a significant advance to our knowledge of desert geomorphology can be made by examining the interactions between slope, surface form and the influence of formative processes on the evolution of this environment.

Several attempts have been made to model the behaviour and development of coarse clastic surfaces (Ahnert, 1994; Tribe and Church, 1999). Although commonly simplistic, modelling has been found to generate alternative explanations of geomorphological features which cannot be described by a conventional reductionist analysis (Harrison, 2001). Non-linear behaviour and the development of emergent properties in landscape are two examples amongst many (Phillips, 1999). The intricacies of the environment studied in this thesis lend themselves to this alternative approach. With a detailed understanding of form and process tentative suggestions about surface dynamics and slope evolution can be made. The data can be applied to explore wider theories of the behaviour and dynamics of earth surface systems.

1.3 The northeastern Jordanian Badia

The area studied within this thesis is the northeastern Badia desert of Jordan. This environment, dominated by extensive lava flows of the Harrat Ash-Shaam Basaltic Super Group, has historically been viewed as a hostile environment. Some refer to the region as Bilad esh-Shaytan, or the Land of the Devil (Helms, 1981). Bender (1968) described a complex series of intercalated basalts of various ages and mineralogies. The lava flows are comprised of a suite of basalts that have created a complex mosaic of distinct land surface configurations (Allison *et al.*, 2000). The basalts emanate from the north in Syria at Jebel Druz and traverse contemporary boundaries to reach the margins of the Nafudha Desert 180 km to the south in Saudi Arabia. The region, defined by the limits of the basalt flows, represents 11,200 km^2, which is over 14% of Jordan's land mass (Dutton, 1998).

1.4 Organization of the thesis

The thesis begins with a detailed discussion of the geomorphology of the northeastern Badia (Chapter 2). Questions with regard to the contemporary geomorphology of the region are raised, providing a context for the research presented in this thesis.

Chapter 3 describes the sampling methodology used. In a landscape where variations in surface form are subtle an appropriate method of sample site selection is required. A nested series of scales upon which the research is based is developed, allowing the results of plot-based studies to be considered and extrapolated to the wider landscape. A full description of the sample sites is provided.

Chapter 4 explores the relationships between surface form and slope. A new automated aerial digital image analysis technique is developed, which generates highly detailed measures of the *in situ* character of the surface form. The results generated are found to perform more favourably than conventional measures of surface form previously used both in the northeastern Badia and beyond. Relationships which examine the influence of slope controlled processes, specifically surface hydrology, in modifying the surfaces are explored. The results generated are considered in the context of whole slope profile.

Chapter 5 presents the first study of slope hydrology on the surfaces of the northeastern Badia. A series of rainfall simulation experiments have been undertaken which examines the role of hydrological activity. The results are used to demonstrate the control of local surface configuration and whole slope profile form on surface hydrology. The data collected are designed to provide a vital understanding of rainfall partitioning and runoff generation in the northeastern Badia.

Chapter 6 develops a cellular automata model to understand the spatial modification of clastic surfaces in arid environments. The surface characterization (Chapter 4) and experiments on surface hydrology (Chapter 5) identify several features of the landscape which show non-linear behaviour that cannot be explained by conventional reductionist approaches. A model, which simulates the movements of surface clasts and the structures which they form as a self-organizing system is developed. The dynamics of the surfaces observed in the field are tested against a hypothesis of iterative surface modification using the model. The results have significant implications for the understanding of the dominant controls and interactions on coarse clastic desert surfaces. Additionally, the results are used to assess the value of self-organizing systems as a geomorphological tool.

Chapter 7 provides a concluding synthesis of the findings of the surface characterization, surface hydrology and modelling. The original contribution made by this research is discussed and the advances made to previous research are described. In conclusion recommendations for further study are made.

1.5 The Jordan Badia Research and Development Programme

The pressure of rapid population growth and the need to develop the more inhospitable extremes of Jordanian territory, including the northeastern Badia, led to the formation of the Jordan Badia Research and Development Programme (JBRDP). The programme was established in 1994, under the aegis of the Higher Council for Science and Technology in Jordan and the Royal Geographical Society with the Institute of British Geographers in the UK (Dutton, 1998). The remit of the project is to gain a better understanding of the natural resources of the northeastern Badia and use this as the basis to guide future sustainable development to the benefit of the local population. This thesis contributes to ongoing research into the understanding of the natural environment of the northeastern Badia. The field research conducted within this thesis was only made possible by the kind assistance of the JBRDP and the staff at the Safawi Field Centre and in Amman. It is hoped that the findings, in addition to their contribution to geomorphology, will be complementary to the remit of the JBRDP.

Chapter 2: The physical environment of the northeast Badia

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Rates of geomorphological change, the subtlety of spatial variations in process-form relationships and the hostile nature of the Badia environment have resulted in a limited understanding of the region. Issues arising from previous work fall into three categories. First, there is a need to quantify the variations in landforms. Second, processes are poorly understood. Slope hydrology and hydraulic erosion are important in modifying the landscape but there are limited quantitative measures of activity in the field. Third, the link between form and process and the evolution of the environment is not well understood. Several characteristics of the landscape show a subtle link between form, process and land surface age.

2.1 Field site location

The arid margin of Jordan, termed the Badia, extends from Saudi Arabia in the south to Syria in the north. The western limit is the Rift Valley Mountains, while to the east is the border with
environment with little or no permanent vegetation, infrequent precipitation and intermittent surface water (Allison *et al.*, 2000). Another commonly used term is Al-Idrisi: a terrain mantled with stone, steppe and sands (Starky and El-Daly, 2000). The Badia region is diverse and can be sub-divided into distinct areas: the Arhd es-Sawwan (the Lands of Flint) in the west; the al-Hamad limestone and chert plains in the east; and the sand flanks of Wadi Rum and the Nafudha Desert to the south (Betts, 1998; Helms, 1981). This study is concerned with the northeast Badia, known locally as the Harrat or Hauran, meaning rocky lava field. The region is characterized by low undulating hills which are covered by basalt boulders. The study area encompasses the Harrat basalts, which fall within the present borders of the Hashemite Kingdom of Jordan, (Figure 2.1 and Figure 2.2). The environment, dominated by the extensive lava flows of the Harrat Ash-Shaam Basaltic Super Group, or North Arabian Volcanic Province, has historically been viewed as a hostile environment. Some refer to the region as Bilad esh-Shaytan, or the Land of the Devil (Helms, 1981). Bender (1968) termed the region Nordostjordanische Deckenbasalte, describing a complex series of intercalated basalts of various ages and mineralogies. The lava flows are comprised of basalts that have created a complex mosaic of distinct land surface configurations (Allison *et al.*, 2000). The basalts emanate from the north in Syria at Jebel Druz and traverse national boundaries to reach the

margins of the Nafudha Desert, some 180 km to the south in Saudi Arabia, flanking the Azraq and Sirhan depressions to the west and east respectively. The region, defined by the limits of the basalt, represents some 11 200 km^2, which is over 14% of Jordan's land mass (Dutton, 1998). Described as an island within the deserts of the apex of Arabia, the region's harsh terrain has constrained travel (Helms, 1981). The Black Barrier has been seen as a deterrent to passage and also to scholarly study (Baly and Tushingham, 1971; Helms, 1981).

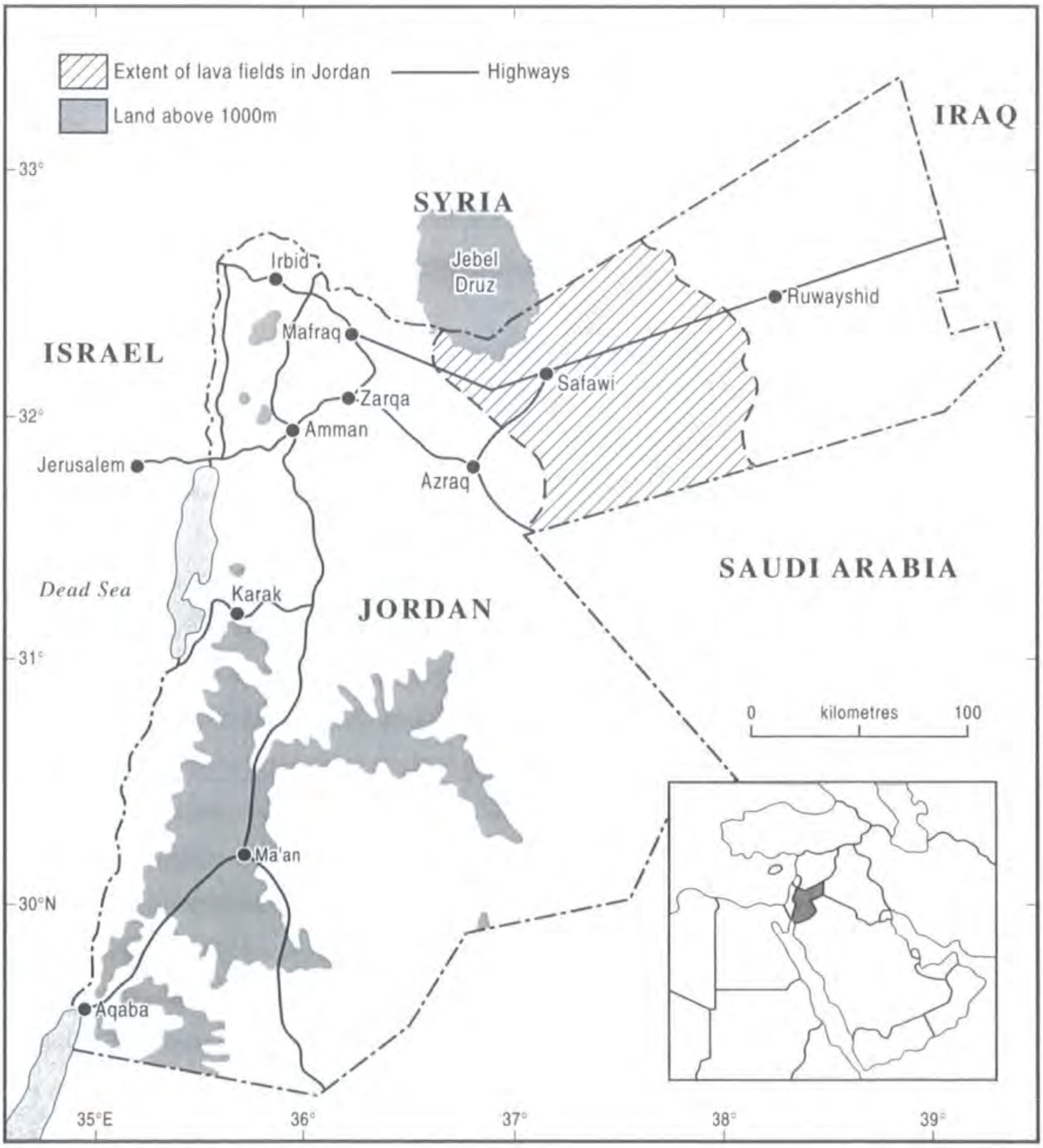


Figure 2.1 Location of the northeastern Jordanian Badia desert

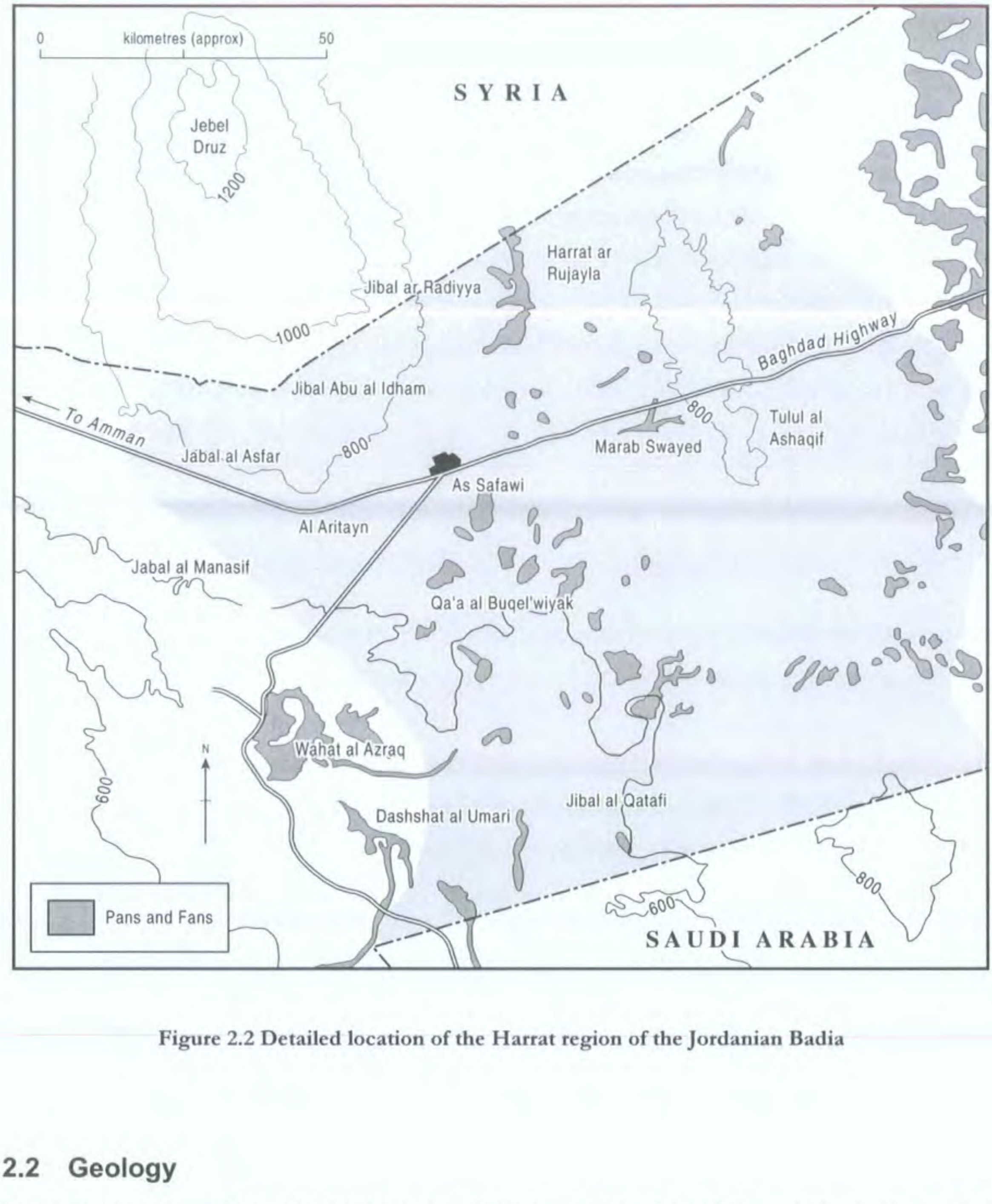


Figure 2.2 Detailed location of the Harrat region of the Jordanian Badia

2.2 Geology

At the regional scale the stratigraphy and structure is complex. The surface geology of the exposed rocks is relatively simple and well understood (Bender, 1968; Tarawneh *et al.*, 2000). The Arava Rift and the associated phases of deposition of sedimentary and igneous rocks have formed a diverse regional geology. The stratigraphy and structure are closely related. A detailed history of the geological setting of the region is beyond the scope of this thesis but comprehensive discussions are presented by Bender (1968), Burdon (1959) and Quennell (1951). What follows is a brief description of the geological succession and key periods of geological activity which have had an influence upon the northeastern Badia and are relevant to this study.

2.2.1 Geological stratigraphy and history

Sedimentary rocks cover most of Jordan, with rock depth increasing to the north and east where progressively younger sediments are exposed (Allison *et al.*, 2000). Plutonic and metamorphic rocks are exposed in the far south of the country (Bender, 1974). The country represents a transition between distinct geological units. A stratigraphic column of the geological succession in the northeastern Badia (Figure 2.3) illustrates the range of exposed deposits across the country and is vital for understanding the context of the northeastern Badia.

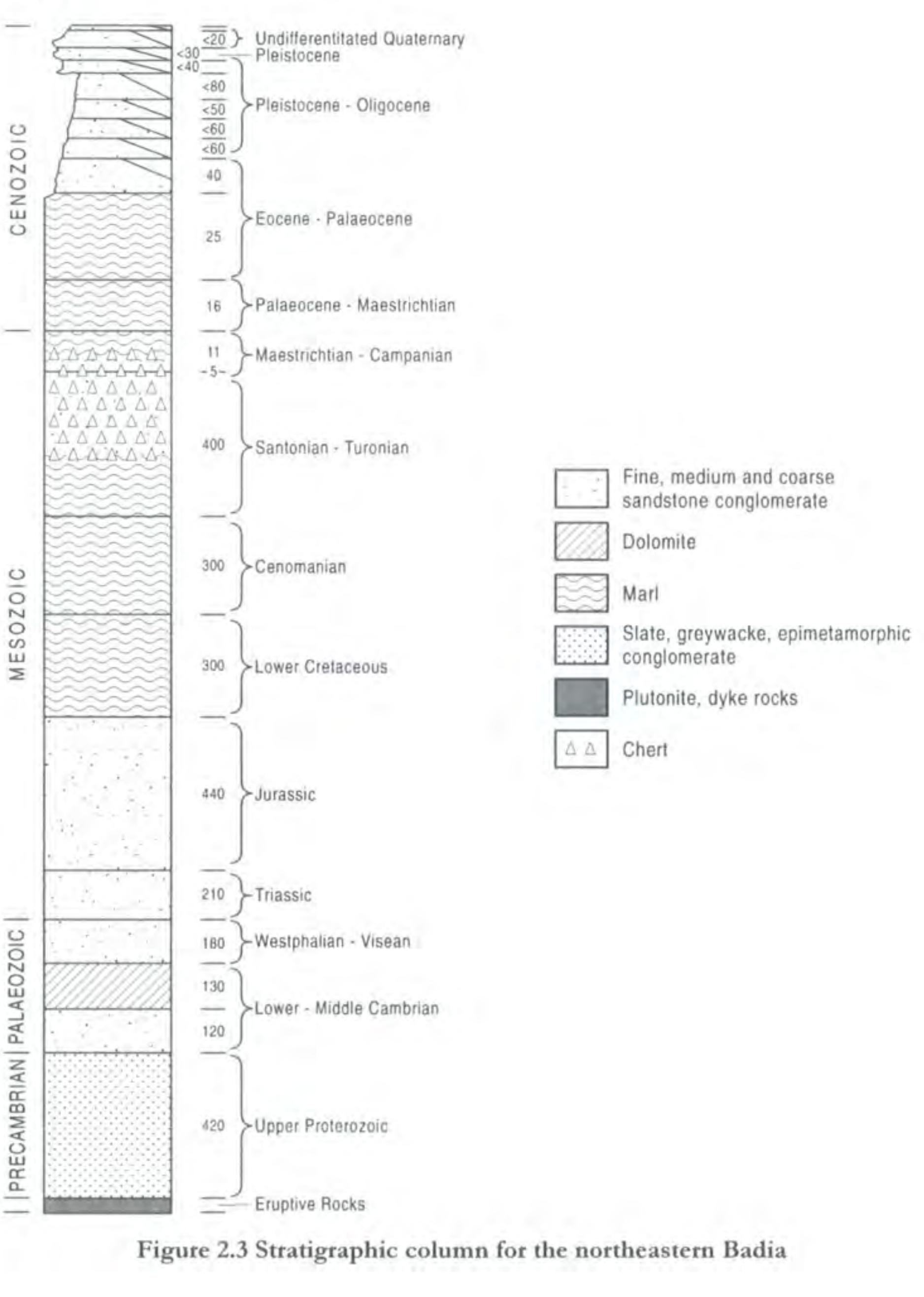


Figure 2.3 Stratigraphic column for the northeastern Badia

Terrestrial sedimentation was limited until the Late Jurassic and early Cretaceous, after which the Kurnub sandstones were emplaced over the entire area within the Jordanian borders. The Kurnub sandstones are poorly consolidated exposures of the Nubian type sandstone, identified by Shaw (1947) in Wadi Hathira and later further east by Quennell (1951). Gradual marine transgression by the Bitlis Ocean during the Cretaceous, a part of the Tethys Sea, laid down interbedded limestones and marls, termed the Ajlun series; the deepest deposits of the Ajlun series beds are found to the northwest. They thin to the south and to the east. Above the Ajlun series is the Belqa series, a result of constant sedimentation throughout the Upper Cretaceous, Palaeocene, Eocene and into the Oligocene. The period of deposition of the Belqa series was characterized by terrestrial emergence. The period experienced tilting, uplift and the formation of likely peneplanation surfaces which today slope into the Wadi Sirhan depression (Allison *et al.,* 2000). Sedimentation continued from the Mesozoic era into the Cainozoic, with no break in the sedimentary sequence. Clastic and marine carbonates, comprising marls, limestone and dolomitic limestone characterize sedimentation from the period. Carbonate deposition continued into the Tertiary and Quaternary providing the sequences that today form one of the region's major aquifers.

The most important units in terms of the contemporary geomorphology of the northeast Badia are the Late Tertiary and Early Quaternary Lava fields of the Harrat (Guba and Mustafa, 1988). The deposition of lavas occurred in two dominant periods. The first phase bridged the Late Oligocene and Early Miocene. The lava flows of this period were intrusions of transitional to theolitic basalts. The second, more extensive, period produced many of the expansive lava fields present today. The basalts are mildly to strongly alkaline and responsible for much of the topography (Tarawneh *et al.,* 2000). The stratigraphy of the Badia has various geomorphological implications. The proximity of unconsolidated sedimentary deposits presents an extensive source of aeolian material. Of note are the Hammada to the east and northwest and the Nafudha Desert to the south. Second, the stratigraphy supports aquifers which can influence the surface hydrology and hence geomorphology. Third, and most importantly, the basalt lava fields dominate the landforms of the region.

2.2.2 Structural geology

The structure of Jordan is dominated by the Dead Sea Rift System (Quennell, 1956, 1984). The influence of the plate boundary propagates beyond the limit of the rift valley itself (Burdon, 1959). There have been two main periods of structural instability. First, a northerly displacement of 62 km during the early Miocene, and then a second, movement of 45 km during the late Pliestocene (Burdon, 1959), identified by Quennell (1951) from the lateral displacement of wadi incisions. Palaeomagnetic data confirms this two-stage movement of the Arabian plate and the subsequent vulcanicity seen in the Harrat (Barberi *et al.*, 1979). There is some debate about the timing and magnitude of the movements (Burdon, 1959) but the influence of the rifting dominates the regional structural geology. Large scale rifting and the associated sinistral strike slip faulting which developed on the eastern flanks of the rift valley are central to understanding the evolution of the basalt surfaces of the Harrat.

The Oligocene witnessed uplift followed by tilting of marine sediments to the east. Drainage has since rejuvenated, feeding both west into the Jordan Valley and east into the Wadi Sirhan depression. Each successive downward movement and opening of the rift system has adjusted the river base level, capturing drainage systems that previously fed Wadi Sirhan and the El-Jafr Basin (Beheiry, 1969). Lateral faulting is apparent, oriented away from the Jordan Valley east into the Badia. East to west faults are traceable for distances of up to 50 km, and north to south striking slip fracture zones are present (Quennell, 1984). Faults channel dyke intrusions which act as conduits for igneous material. Fault sets tend to focus volcanism and concentrate the development of dykes into linear features. Dominant fault directions are east-to-west, northwest to southeast and east-north-east to west-south-west. Though vertical displacement is not pronounced, present day drainage patterns are controlled by geological structure (Guba and Mustafa, 1988). The basalts of the Badia not only comprise flood basalts which emanate directly from the Druz complex in Syria, but also locally extruded dykes sills and volcanic cones (Figure 2.4).

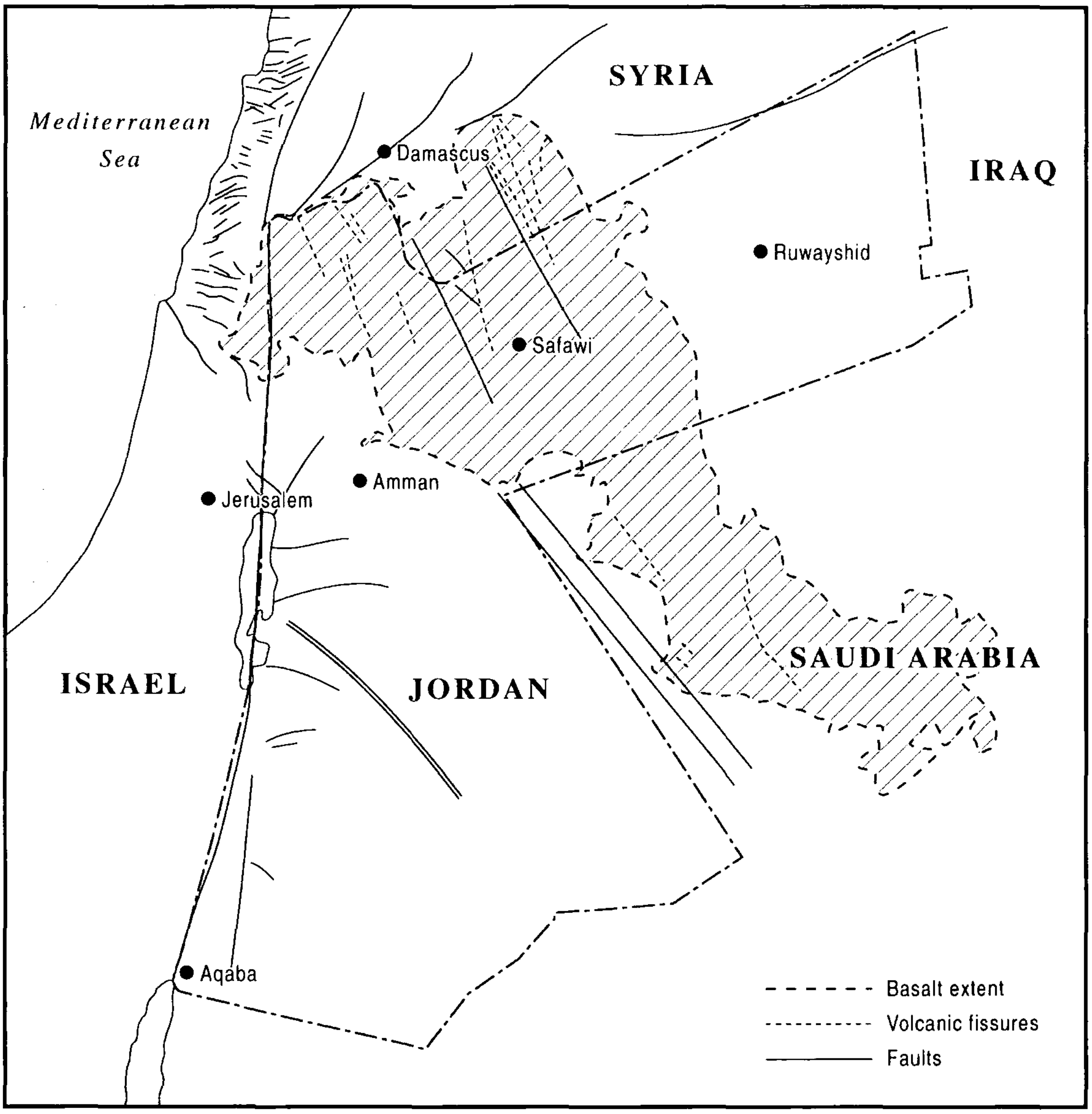


Figure 2.4 Structural Geology of Jordan (after Quennell, 1958)

2.2.3 The Harrat Ash-Shaam Super Group

Moffat (1988) has shown that there were extensive extrusive basaltic eruptions throughout Syria and northern Jordan from as early as 13.7 ± 0.7 Ma. Activity continued to less than 0.1 Ma. Carbon-14 dating of organics found within recent basalts places minor events to less than 4000 years B.P. at Jebel Druz (De Vries and Barendsen, 1954). The plateau upon which the flows have been laid is bounded to the west by the Golan, which stretches eastwards to the southern edge of the Damascus Basin. Bender (1968) proposed a chronology of basalt emplacement in the region. The initial flows originated from fissures and are alkali olivine in nature. The resulting deposits were thin and horizontally bedded. Later flows were more viscous and are responsible for the present day local relief emanating from the dominant south-southeast to north-northwest striking faults (340°), at an angle normal to the south Palmyra zone of faulting (Quennell, 1984).

The resulting wedge of basalt is some 1500 m thick in southern Syria and gradually reduces in depth as it flanks the eastern margin of the Sirhan depression in Saudi Arabia. Quennell (1984) suggests the loading inferred by the basalt would have been considerable and may have encouraged under-thrusting. Various attempts to create a chronosequence of basalt flow emplacement have been made (van der Boom and Suwwan, 1966; Bender, 1968; Quennell, 1984; Guba and Mustafa, 1988; Ibrahim, 1993; Tarawneh *et al.*, 2000; Ilani *et al.*, 2001). The formation comprises a complicated series of discrete flows, each with a distinct mineralogy. A summary of these studies shows a complex series of groups and subgroups of flows (Table 2.1). In the field further differentiation between the surface characteristics of individual flows within one basalt type is apparent.

Formation (after Tarawneh *et al.*, 2000)	**Group**	**Classification** (after Bender, 1974)	**K – Ar age** (after Moffat, 1988 and Tarawneh *et al.*, 2000)	**Geological period**		
Fadha Vesicular Basalt (FA)	Bishriyya (BY)	B6/5	0.1 – 1.45 Ma			Quaternary
Wadi Manasif Basalt (WMF)		B6				
Aritayn Volcaniclasics (AT)	Rimah (RH)	Bt	2.01 – 2.94 Ma	Neogene (Late Tertiary)	Miocene	
Hassan Scoriaceous (HN)		Bt				
Mahadda Basalt (M)	Asfar	B5	1.96 – 3.41 Ma			
Madhala olivine Pyric Basalt (MOB)		B5/4				
Hasimyya Aphanitic Basalt (HAB)		B5				
Ushayib Olivinv Pyroxene Pyric Basalt (UB)		B5				
Ufayhim Xenolithic Basalt		B6/5				
Salaman Flood Basalt (SN)	Safawi (SW)	B5/4	8.45 – 9.3 Ma		Pliocene	
Abed Olivine Pyric Basalt (AOB)		B5				
Ali Doleritic Trachytic Basalt (AI)		B5				
Continental / Marine Sedimentation Quirma Calcareous Sandstone Formation	(QCS)	tt4				
	Wisad (WD)	B4	9.37 – 10.53 Ma			

Table 2.1 A summary of the Harrat Ash-Shaam Super Group of basalts (after Tarawneh *et al.*, 2000)

Today the basalts retain the lateral extent of their original emplacement. Flows lineate around fault systems and create dendritic and lobate forms where they pinch out (Figure 2.5). The basalt surface cover is continuous, interrupted in the landscape by wash and aeolian sediment deposits in topographic lows and lower reaches of drainage networks.

Basalts can be differentiated both through petrology and age but also surface character and appearance on the ground (Saffarini *et al.,* 1985; Allison *et al.,* 2000) and from remotely sensed imagery (Tansey, 2000). The basalts exposed at the surface comprise basic lava flows, dyke systems, pyroclasts, and volcanic centres, including shield and strato-volcanoes, fissure effusions, chains of volcanoes, maars, tuff pipes and flood lava (Bender, 1958; Ibrahim, 1993; Tarawneh *et al.*, 2000).

The research presented in this thesis considers a selection of basalts which are chosen on the diversity in surface character and slope form variation. The geological characteristics of the basalts are in part responsible for their present day surface form. The selected basalts have a range of ages (8.9 Ma to less than 0.1 Ma) and a range of mineral compositions. The basalts under consideration in this study are the Abed, Madhala and Bishriyya, in addition to the previously studied Salaman and Scoriaceous deposits (Table 2.2).

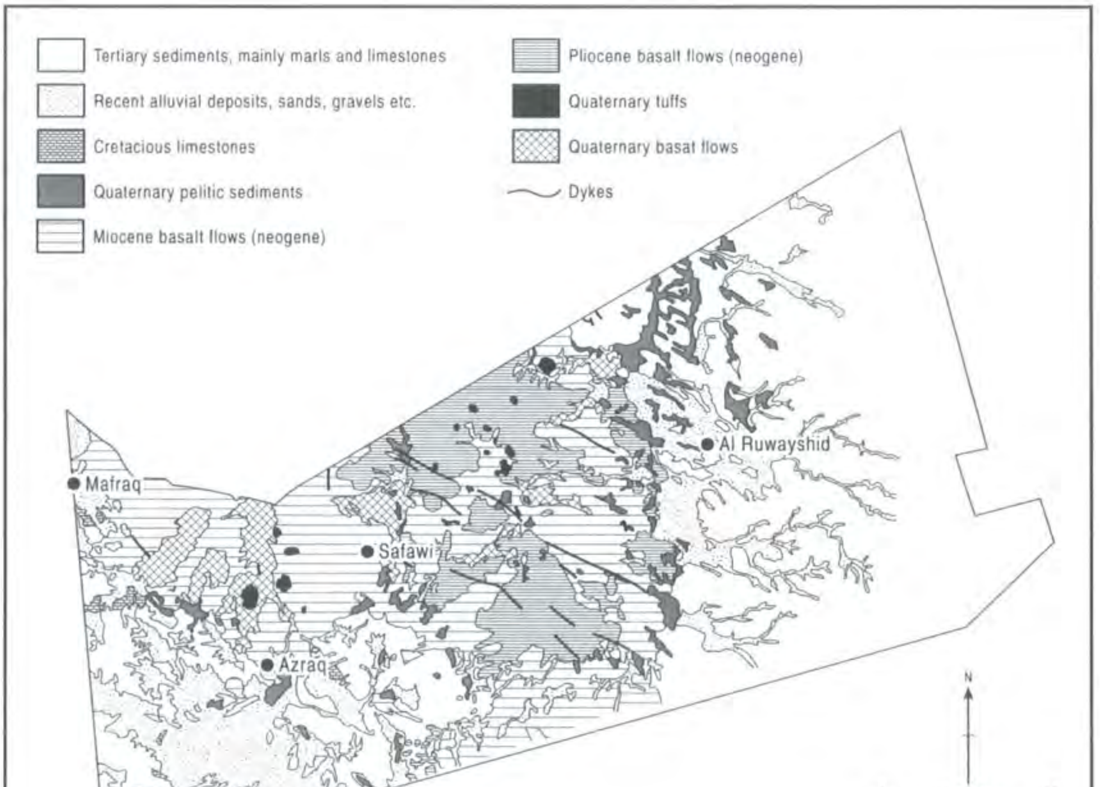


Figure 2.5 Map of the geology of the study area

Basalt	Age	Characteristics
Abed	8.9 Ma	Olivine picric mineralogy. Large angular boulder with b-axis 0.3 m - 0.4 m underlain by loose orange fine sediments. Mineralogy is principally olivine phyric, holocystalline, porphyritic and typically microvesicular in texture. Minerals include olivine, plagioclase and pyroxene, apatite and zircon.
Salaman	8.45 Ma	Extensive but thin flood basalt. Surface dominated by small basalt clasts interspersed by a few larger clasts. Virtually no exposed sediments. Highly weathered. Fine grained holocrystalline with porphyritic and amygdloidal textures. Very similar mineralogy to Abed
Madhala	1.96 – 3.41 Ma	Olivine picric. Medium sized clasts, with sediments exposed between fragments. A fine to medium grained melancratic, vesicular-amygdaloidal, porphyritic basaltic lava. Mineralogy is comprised mainly of microphenocrysts with some iddingsite and serpentine.
Bishriyya	0.1 – 1.45 Ma	Large ridge of intact vesicular bedrock. Surface are dominated by large clasts with spaces occupied by smaller, more angular clasts. Comprised of olivine phenocrysts and plahioclase, with trachytic and variolitic textures.
Scoriaceous deposits	< 0.5 Ma	Found around the more recent volcanic cones. Highly vesicular basalt of olivine iddingsite phyric composition olivine.

Table 2.2 Basalt types and mineral properties (after Tarawneh *et al.,* 2000)

2.3 Climate

2.3.1 Regional Climate

Jordan represents a zone of transition between the diverse environments of the arid interior of the Arabian Peninsula, and the eastern Mediterranean. The region is characterized between Saharan-Arabian and Syrian Steppe (Dutton, 1998). In Köppen's classification the region is represented as BWhs and BShs (Lamb, 1972), where B is dry climate, BS is steppe, BW desert, dry season in summer, and h dry and hot with mean annual temperatures over 10°C. The moisture scale in the area is considered semi-arid to arid, with temperatures commonly in excess of 38°C, mirrored by equally large diurnal temperature variability.

Seasonal variations in the climate of the region are attributed to large scale meteorological fluctuations, dictated by the seasonal geographic displacement of weather systems (Wigley and Farmer, 1982). The wet winter season is characterised by cyclonic disturbance and low pressure over the Mediterranean. Higher pressures further east associated with the Siberian high dominate climatic patterns via a shift in the Polar Front Jet stream allowing the transport of cold air to the region (Perry, 1981). During the spring the Subtropical Jet Stream migrates north from the Tropic of Cancer. This pushes associated cold air masses into the region, reducing precipitation. During winter and spring 'Cyprus Lows' dominate precipitation characteristics over the north Arabian peninsular (Krown, 1966; Lamb, 1968). Generally, if subsident conditions persist over Cyprus, then dry winter conditions prevail over the Middle East but if cyclonic conditions move east, westerlies predominate and precipitation occurs. Orographic effects are of particular importance under these conditions (FAO, 1962).

During early summer the influence of the Polar Front and its associated westerlies is negligible. The influence of sub-tropical ridges of high pressure becomes dominant. Convergence of strengthening easterly jet streams is associated with upper air convergence causing widespread subsidence across the Middle Eastern desert areas. The summer and winter months are considered to have stable climatic conditions but it is the transitional months where significant variation in climate between years is seen. The spring and autumn months are the periods of the year which experience high magnitude storm-events (Perry, 1981).

The region experiences a marked precipitation gradient (Dottridge, 1998). Rainfall decreases from west to east and also from north to south. The east - west gradient is attributable to increasing penetration into the arid Arabian interior, combined with the adiabatic heating of moist westerly air on the lee of slopes bounding the eastern flank of the Jordan Valley. The north - south transition is tied directly to the track of depressions from the Mediterranean (Shehadeh, 1985).

The region is characterized by both large scale high velocity winds and low magnitude daily variations which operate at a more local scale. Large scale events have a significant geomorphological influence across the region. The Khamseen, for example, transports large quantities of sediments (Yaalon and Ganor, 1979). Khamseen depressions arise along the Intertropical Front, originating as Sudanese Depressions, which are then carried to the coast of the Mediterranean by westerlies. In May and June the depressions tend to follow a path north of Nigeria to Lower Egypt and, if they are strong enough, will continue up into the Syrian Desert (Dubief, 1979). Yaalon and Ganor (1979) in a survey of dust storms in Jerusalem noted a dominant source direction of 270° and high wind speeds of up to 60 km h^{-1}. Dust storms have high particulate concentrations of up to 10 tonnes km^{-3}, visibilities of less than 300 m and a spatial cover of over 5 000 km^2. The duration of such storms can be up to 50 h. Mineral analysis found that the sediments could be traced back to the weathering environments of the Sahara. Over 80% of the storms surveyed in Jerusalem were sourced to a southwesterly origin. Many other authors have found similar magnitudes of dust concentration in the region (Dan and Yaalon, 1966; Dubief, 1979; Ganor and Mamane, 1982; Jones *et al.,* 1986).

Easterly winds are rare (Yaalon and Ginzbourg, 1966). Easterlies with velocities of 56 km h^{-1} have been measured, with visibility as low as a few metres. Yaalon and Ginzbourg (1966) concluded that the easterlies are responsible for the movement of large amounts of material over small distances. There has been no attempt to investigate the influence of aeolian transport or erosion of sediments in the northeastern Badia. Analysis of sediments in topographic lows in the northeastern Badia indicates high levels of carbonates and other exogenously derived material.

2.3.2 Climate of the study site

High-resolution data for the period August 1994 to the summer of 1996 collected in the northeastern Badia echoes the temporal pattern of climatic variations on the regional scale (Kirk, 1997) (Table 2.3). Both large seasonal and large diurnal temperature ranges are apparent. Temperature has a profound influence on moisture and weathering regimes and is therefore of importance to considerations of the long-term weathering of the surfaces of the northeastern Badia.

Diurnal temperature range	5 – 32 ^{0}C
Time of lowest hourly temperatures	4 am to 6 am
Highest standard deviation in mean daily temperatures	May (7.5 ^{0}C)
Lowest standard deviation in mean daily temperatures	December to January (3 to 4 ^{0}C)
Highest recorded temperature	47 ^{0}C
Lowest recorded temperature	-12 ^{0}C

Table 2.3 Temperature characteristics of the northeastern Badia (after Kirk, 1997)

Rainfall in the northeastern Badia region is directly related to altitude and distance from the slopes of Jebel Druz (Kirk, 1997). Long-term monitoring since the 1960s indicates a general decrease in the total amount of rainfall but also pronounced annual fluctuations in rainfall totals. The standard deviation at three of the most consistent monitoring stations is in excess of 45% of the mean, though the deviation has tended to reduce in recent years. Orographic effects reduce local scale variability (Kirk, 1997). At sites further from the Jebel Druz foot-slopes, variability in rainfall is less and rainfall totals are more constant attributed to the stabilizing effect of the increased proximity to these sites of the arid interior (Dottridge, 1998) (Figure 2.6). Sites in the north and west of the study area, for example Umm El-Quttayn and Dayr El-Kahf, have high annual rainfalls of 113 mm and 112 mm respectively. Sites further east and south, for example those at Safawi and Azraq, have significantly lower mean annual rainfalls of 76.1 mm and 67.3 mm respectively.

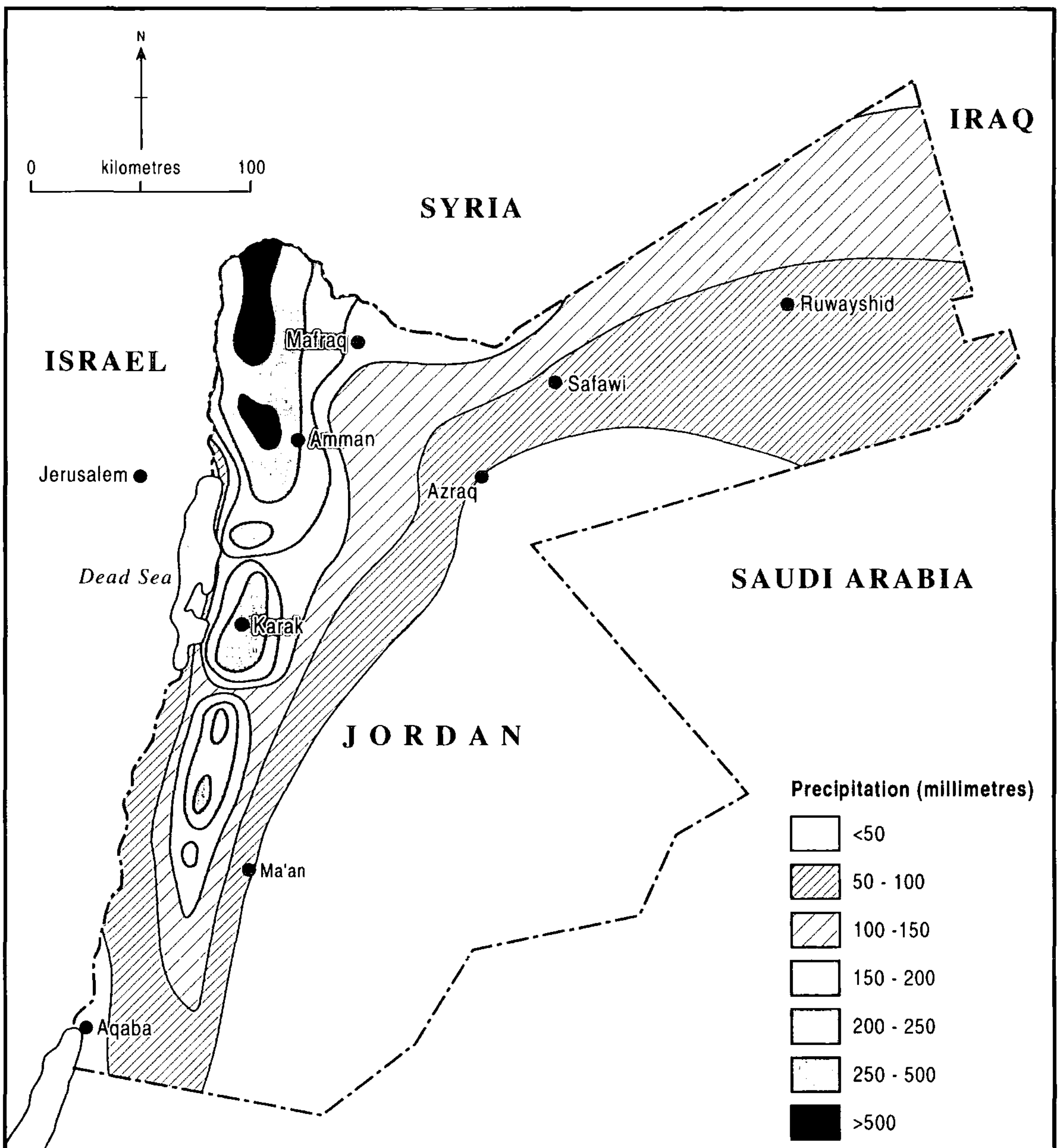


Figure 2.6 Distribution of rainfall across the Badia

Evaporation potential across the region is large, ranging from an annual rate of 1 800 mm a^{-1} to 2 000 mm a^{-1}, resulting in an annual excess of evaporation over rainfall. High magnitude individual storms reverse this general trend. In extreme cases (Kirk,1997), (Figure 2.7) the result is overland flow generation.

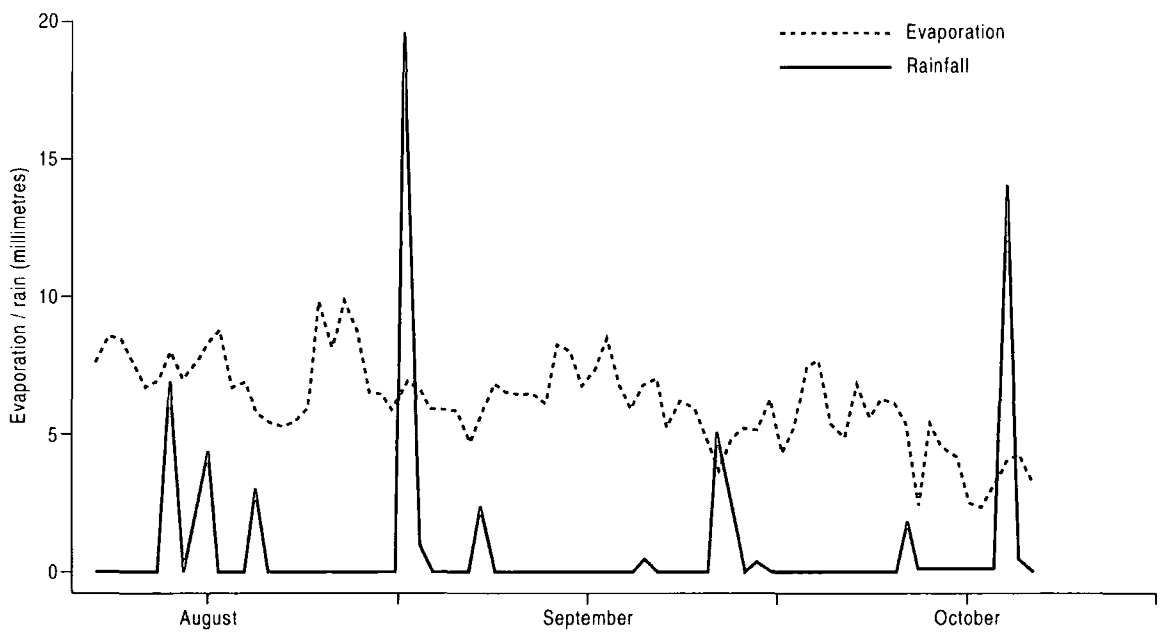


Figure 2.7 Total daily evaporation versus rainfall (1994)

There is a seasonal change in rainfall. The highest-magnitude events occur during the spring and autumn months. The remainder of the wet season is dominated by high-frequency, low-magnitude rainfall events, amounting to longer periods of drizzle with hourly rainfall totals of less than 0.5 mm h^{-1}. High-magnitude events are infrequent and localized and hence data is sparse. Intensities have been measured up to 60 mm h^{-1} (17th January, 1994). Storms rarely last for more than 20 to 30 minutes. Cellular convective storms produce highly localized, high-intensity rainfall. Data shows that the nature of storms is random, both spatially and temporally (Kirk, 1998). The drop size and kinetic energy of rainfall are important for considering the nature of formative events and the importance of antecedent conditions between rainfall events.

Desiccating winds add to the harsh nature of the Badia environment (Allison *et al.*, 2000). Although the region is seen to receive winds from all directions, there are distinct and consistent patterns with both daily and seasonal variability operating over a distinct seasonal split (Kirk, 1997). In the summer months the dominant wind direction is northeasterly, with highest velocities during the evening and night. A significant shift in direction to the northwest follows early morning temperature rises, usually via the north but sometimes via the south (Kirk, 1997). During the winter the wind pattern is considerably different. Nocturnal winds are predominantly from the east and south and only occasionally from the north or west. Daytime temperature rises results in a shift, via the south such that the midday winds are from the south and southwest, which shifts back via the south during the evening. As with temperature, the transitional intervening months experience a combination of often erratic nature of the winter and summer conditions. Wind direction during rainstorm events is often from the northwest (318^{o}), showing the influence of the Mediterranean weather systems on the region's climate. Wind direction is also seen to have a significant control the contribution of aeolian sediment supply and deposition, with diverse sediment source areas surrounding the region. Wind speeds are highly variable and therefore difficult to generalize, even using data at 1 h resolution (Kirk, 1997).

Topographic factors affecting climate are not well understood. The proximity of the massive Arava Rift valley to the west of the study site may act to complicate the topographic controls on local climate. Models of the influence of steep sided valleys on airflow suggest the wind direction can be significantly altered by pressure perturbations induced by the valley topography (Bullard *et al.*, 2000). The influence of thermotopographic anabatic and katabatic winds are also of particular importance, given the dominating slopes and regional temperature gradients associated with Jebel Druz to the north in Syria (Thorson and Bender, 1985). Prevailing winds have also been observed to be channelled by drainage networks in the field, often transporting sediments back up into the catchment. More locally, the distinct surface character of the basalt flows, both in terms of roughness and albedo may be significant in locally affecting wind regimes. The variable roughness of surfaces in arid environments has been established elsewhere (Goudie *et al.*, 1999). Evidence of the local control of surface geomorphology is seen through the formation and persistence of dust devils above the reflective Qa'a surfaces, but their instantaneous collapse when they traverse clast dominated surfaces (Cooke *et al.*, 1993). Dust devils are a common phenomenon in the northeastern Badia.

2.3.3 Climate change

There is no continuous record of climatic variability but cautious inferences can be made from studies undertaken in neighbouring areas. Over the time-scale of the emplacement of the basalts there were periods of wetter and drier climate (Shehaded, 1985). In a comprehensive summary of regional climate change, Roberts (1982) was only able to identify 152 Carbon-14 dates, from the Levant, Iran, Greece, Turkey, Arabian, Egypt, Sudan and the Caucuses. The dates closest to the northeastern Badia region were collected in the Jordan Valley which, due to its tectonic setting, should be considered an anomaly (Neev and Emery, 1967). Archaeological evidence suggests that the area has been regularly populated since prehistory (Garrard *et al.*, 1975). Rain fed agriculture struggles in the present climatic conditions.

Numerous studies in the region have examined climatic change through various approaches. The link between the climate of the northern Arabian Peninsula and Mediterranean Basin has allowed several authors to extrapolate between regions. Advances in techniques, such as thermoluminescence dating, have allowed the study of climate change in, for example, sedimentary features and archaeological sites (Grove, 2000; Mercier and Valladas, 1994; Valladas, 1992). The intensity of geomorphic activity varies with climate. A series of studies have been undertaken in and around the region which have examined the nature of climatic variability during the Holocene (Table 2.4). A tentative suggestion which accumulates work from around the region into a picture of variable geomorphic activity during the Holocene is made in Table 2.5. Table 2.4 demonstrates periods of both increased and decreased geomorphic activity relative to the conditions experienced today. The variation in geomorphic activity has many implications for the understanding of the nature of landforms in the region.

Author	Nature of study	Principal findings
Carmi *et al.* (1971)	Study of silt and clast sequences in marsh deposits in the Sinai at Wadi Feiran,	Dating of deposits to 20 ka suggests considerable reduction in water supply in the area.
Isaar and Briuns (1983)	Combined study of aquifer geochemistry and changes in pluvial-aeolian deposition	Multi annual period of drought, followed by period of higher humidity.
Briuns and Yaalon (1979)	Study of the origin of the Neviot series loess in the southern Negev and Sinai	Alternating periods of moister and drier conditions in the Upper Pleistocene and Holocene. Deposits similar in character to those of the present day Khamseen
Thiede (1978)	Study of planktonic foraminiferal faunas and water temperatures on the Levantine coast	Increased summer and winter sea surface temperatures – at the last glacial maximum at approximately 18^0C and 25 ^{0}C
Moeyersons *et al.* (1999)	Sedimentation in karstic shafts in eastern Egypt	A humid phase, or at least less arid phase in the first half of the Holocene
Abed and Yaghan (2000)	Lisan Pleistocene lake sediments in the Jordan valley	Cole dry climate during the Last Glacial Maximum. Similarities between findings and the monsoon conditions which affected North African Sahara, Arabia and South East Asia – *a good possibility of monsoon rain reaching the interior of the southern Levant* (p. 31)
Touchan and Hughes (1999)	Dendrochronology at sites around Jordan	Short 3 to 4 year periods of drought
Neev and Emery (1967)	Dating of the Dead Sea valley floor	Distinct wetter and warmer conditions 17 ka – 10 ka, but complicated by the dynamics of valley rifting and down-faulting
Butzer (1958)	Combined study of historical, archaeological and geomorphological sources	Derives sequence of wet and dry periods, and relates finding to variables rainfall
Hukriede and Wiesemann (1968)	Study of calcareous sediments at El Jafr, central Jordan Badia	Date of sedimentation phase to 27.7 ± 0.870 ka, corresponding to the middle of the Late Pleistocene Glacial
Kaiser *et al.* (1973)	Damascus Basin – stratigraphic study	Last glacial maximum dominated by a cold dry climate
Goodfriend and Magoritz (1988)	Damascus Basin – study of pedogenic carbonate nodules	Last glacial maximum dominated by a cold dry climate

Table 2.4 Studies into Holocene climatic change in the field area and surrounding region

Years B.P.	Climatic description	Geomorphological activity (Greater / Lower)
16000	Period following the close of the Pleistocene wet period. Aeolian processes dominant. Temperatures and rainfall lower than at present, reaching a minimum at around 14000 B.P.	▽
12000	A period of increased precipitation, witnessed a readvance of the ultimately disappearing Pleistocene glaciers, with lower temperatures to at least as far south as 33°N.	↑
10500 – 8800	A humid relapse associated with the last glacial advance and temperatures increased. Rainfall conditions were typically less than those of the present.	△
8800 – 7000	Markedly more precipitation throughout this period.	↑
7000 – 4400	The Neolithic moist period. Higher rainfall than at present, in addition to higher local temperatures. If evaporation was correspondingly high then conditions were effectively Pluvial. There were notable sudden decreases in rainfall shortly after 5,600 and 4850 B.P.	↑
4400 – 2850	Decrease in precipitation during the 5th millennium B.P. led in to a long period of variable climatic conditions. Average rainfall slightly less than that of today, interrupted by one distinct moist spell around 3,200 B.P.	↓
2850 – 1200	Similar rainfall as today, but characterised by marked small fluctuations. Periods of higher humidity occurred around 1,800 and 1,500 B.P., but were opposed by drought conditions, notably around 1,400 B.P.	↓
1300 –	Short term fluctuations with average rainfall higher than present. Cold spells caused the Black Sea and Nile to freeze (1,000 B.P). The last century has seen a marked climatic deterioration, with rainfall decrease of between 1 and 15 %, a fall in lake levels and a decrease in the volume of the Nile.	↑ (Present conditions)

Table 2.5 Holocene climate change and relative geomorphic activity

The effects of climate variations can be considered in terms of the geomorphology of the northeastern Badia. Oberlander's (1972) study of similar basalt surfaces in the Mojave Desert, California, suggested that the geomorphology of rock-mantled slopes may well present relic features of a previous climate. Dating of sediment deposits, combined with the summary of recent regional climatic variations, suggests that during the recent past rates of geomorphological change may have been higher than at present.

Grove (2000), in a preliminary study into the palaeo-environmental change in the northeastern Badia, used detailed stratigraphy calibrated with thermoluminescence dating through a core of in-washed sediment pan (Qa'a) deposits. Coarse inter-bedded clastic deposits and fining-up sequences were noted throughout the 4 m of the stratigraphy. The date at the base of the Qa'a, at the contact with the underlying bedrock, was 18 ka. No clear periodicity in sediment deposition was noted from the section, reflecting the sporadic nature of formative events. Process action at or shortly after the last glacial maximum may have been of sufficient magnitude that all previously in-washed sediments were removed. If this is the case it may be reasonable to assume that such an intensity of processes would also be capable of significantly altering the surfaces of any previous climatic controlled ground surface configuration. Any variation in surface configuration may be a reflection of process action since the last glacial maximum and not as a direct time dependant change incurred by basalt age, as proposed by Allison and Higgitt (1998). This may explain the poor relationship between surface configuration and basalt age.

2.4 Geomorphology

The present day geomorphology must be examined within the context of recent and long-term climatic fluctuations (Allison *et al.,* 2000). For example, warmer and moister climes may have encouraged a more active weathering regime (Bull, 1991). Desiccation of exposed basalt and additional moisture in the soil would have promoted accelerated rates of bedrock weathering. Ghost stones and deep-rooted weathering profiles in the field are potential evidence of this (Allison *et al.,* 1993). The discussion here focuses first on topography, then defines a geomorphological classification of the region and finally goes on to examine slope forms and soils.

2.4.1 Topography

Topographically the region is characterized by low undulating, rounded hills. Local relief ranges from 7 m to 50 m. Relief appears to be linked to the age and lateral extent of the basalt flows (Allison and Higgitt, 1998). Elevation differences across the basalt plateau are pronounced, ranging from 1200 m above sea level in the north on the foot slopes of Jebel Druz, with a decline in absolute relief to less than 400 m above sea level on the Saudi Arabian border in the south. Isolated volcanic centres such as Jebel Al-Arityan (32^{o} 05' N 36^{o} 52') form localized topographic highs up to 100 m above the surrounding ground. Landsat TM images show the lineation of such peaks along structural faults and fissures (Figure 2.8). The undulation of the present ground surface is a reflection of the initial form of the coalesced basalt flows and the subsequent evolution of drainage networks. Development of wadi, networks which feed into topographic closed depressions, is directly related to basalt age. Greater levels of connectivity, local relief differences and sedimentation occur on the older basalts, again a feature which can be identified from the Landsat TM image (Figure 2.8). The north - south relief difference dictates drainage. Wadi Rajil rises in the Syrian hills and flows through Jordan, often being directed by basalt levees parallel to the margins of contiguous lava flows, whose route is structurally dictated.

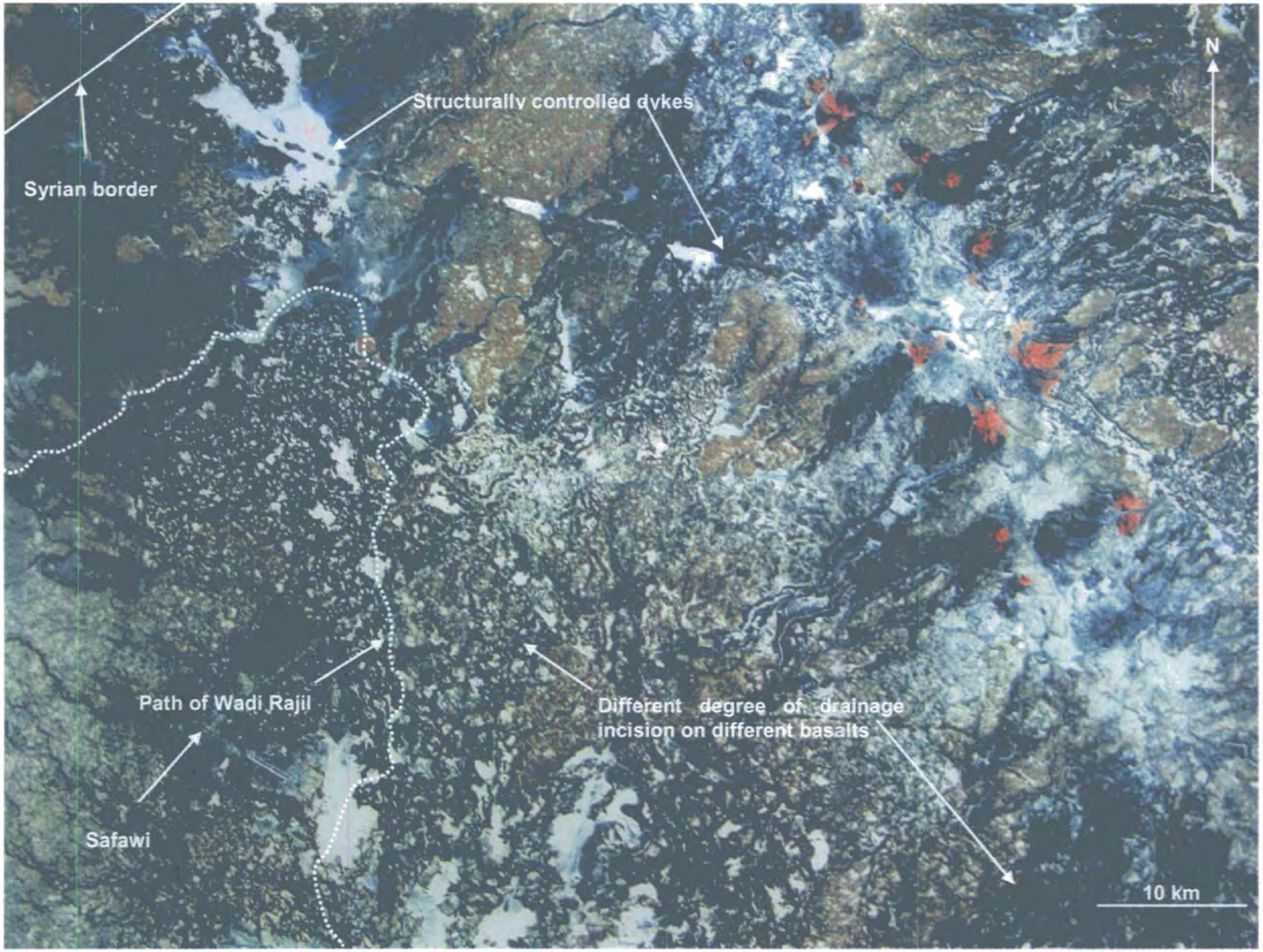


Figure 2.8 LandSat TM - Safawi – and surrounding area of northeastern Badia- Bands 7, 4, 2; path 173, Row 32.12N, Date 29.03.92 (Huntings Technical Services)

2.4.2 Geomorphological classification

Geomorphologically the landscape can be split into two fundamental units: the slopes and the sediment deposits in topographic lows (Allison and Higgitt, 1998). The whole landscape can be further sub-divided into a number of geomorphological units (Figure 2.9).

Slopes are dominated by a coarse, clastic boulder cover. For the purposes of this study, basalt surface blocks are referred to as clasts and the underlying fines are termed sediments. The surfaces present an open matrix with large, well varnished, rounded clasts (Plate 2.1 and Plate 2.2). The undersides of clasts are commonly clad with a saucer shaped carbonate accretion. In places clasts are covered with lichens but there is a clear gradient in the abundance of lichens based on topography and rainfall. Lichens locally have an orientation bias to the north facing sides of clasts. The variation in the configuration of clasts on the surface is complex (Allison and Higgitt, 1998). Variations occur with slope, basalt type, and position within the drainage network. The sizes, degree of rounding, burial and sorting of clasts all vary systematically (Allison *et al.,* 2000). Additionally, the surfaces often exhibit a distinctly non-random clast distribution. There has been no attempt to link the nature of the spatial character of the clasts on the surfaces to basalt type, slope, ground surface cover, or process activity. Closed topographic depressions are in-filled by sediments.

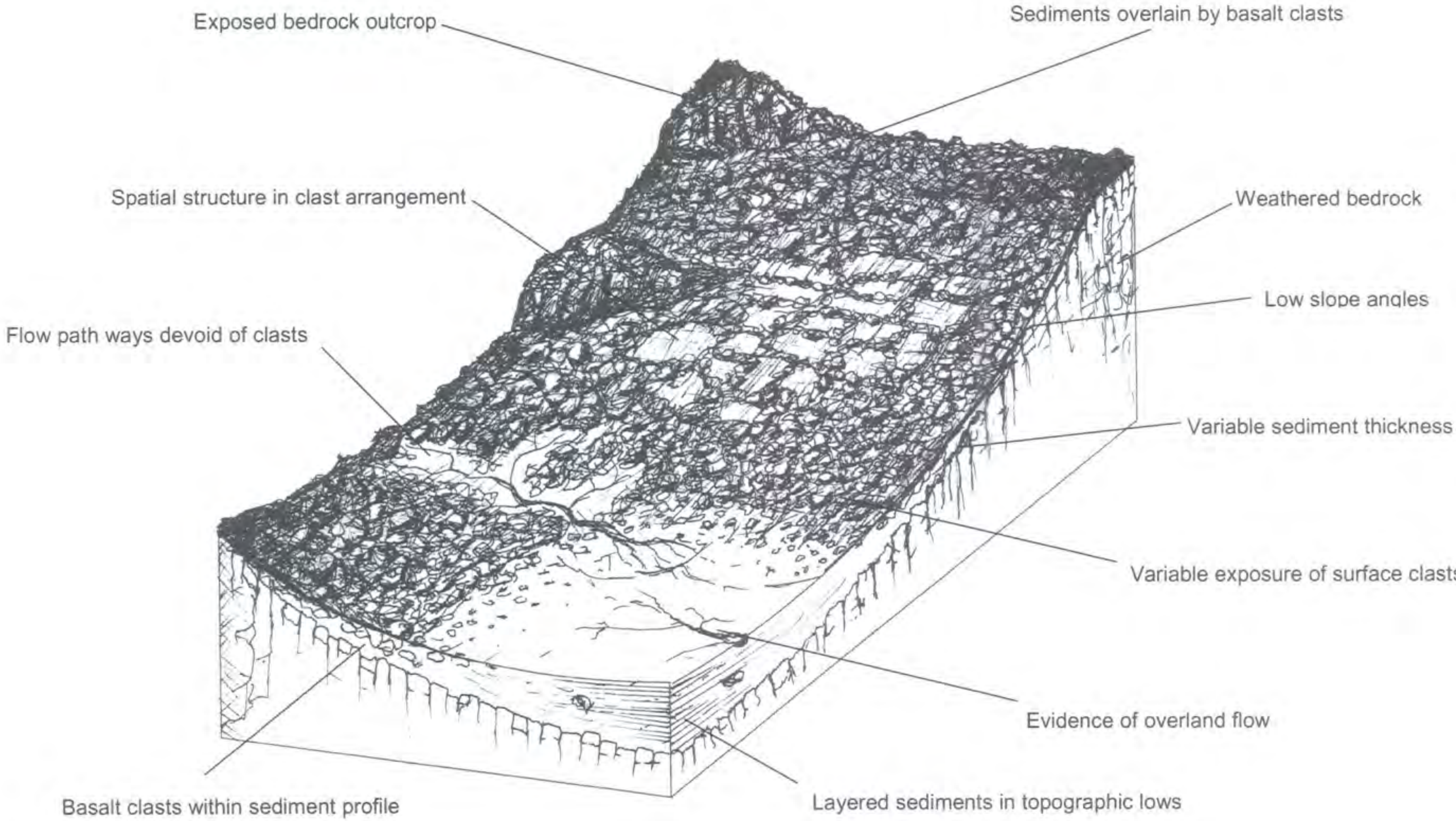


Figure 2.9 Block diagram of the geomorphological attributes of the basalt flow surface of the northeastern Badia

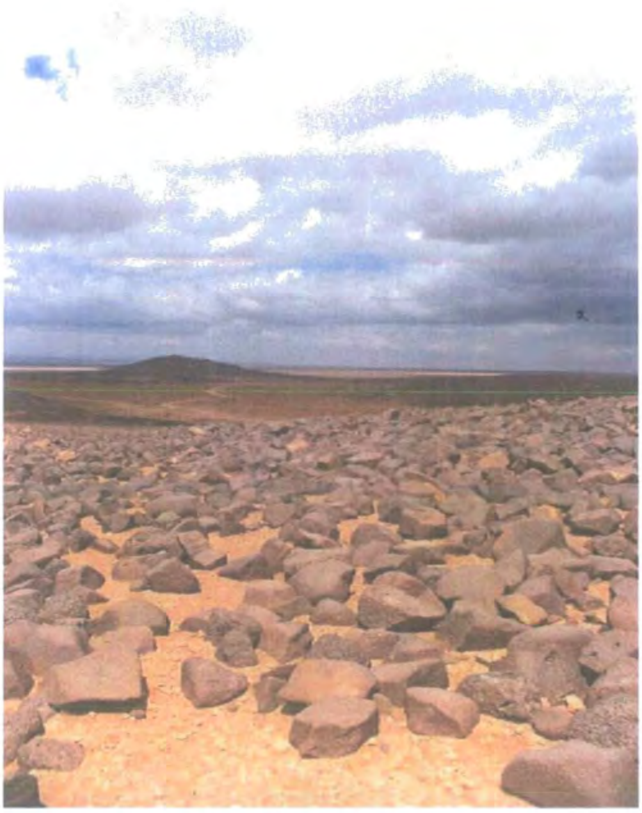


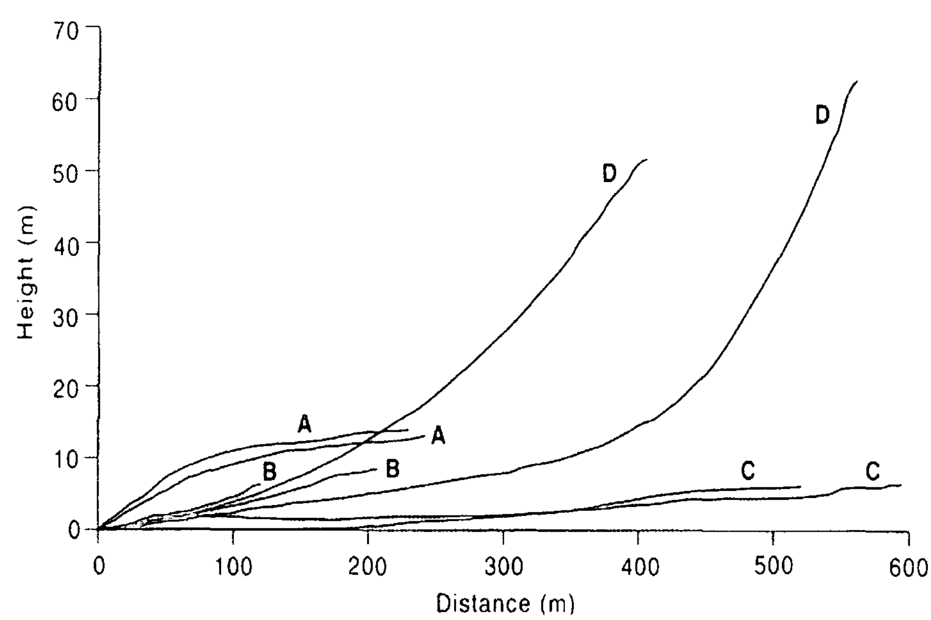
Plate 2.1 General view of the northeastern Jordanian Badia, showing open coarse clast dominated surfaces

Plate 2.2 Isolated volcanic dyke ridge at Qa'a Selma, surrounded by an extensive Qa'a feature

2.4.3 Slope forms

The northeastern Badia has a range of slope profile configurations, which have been linked to geological controls (Allison and Higgitt, 1998). It has previously been suggested that profile form is related to the development of drainage network connectivity and lava ridge denudation (Allison *et al.,* 2000). Slope forms are thought to represent a continuum, from concave to convex slopes with increasing maturity (Allison and Higgitt, 1998). The younger flows show concave slope form. Bishriyya basalts comprise distinct vertical accretions of lava in ridges and sills (Figure 2.10). The Scoriaceous lavas, which represent the youngest deposits, form cone structures with highly concave slopes. The oldest flows of the Madhala and the Abed show more convex profiles. In the context of the overall plateau, slope form changes are associated with lave ridge denudation and the drainage evolution. The rapid weathering of young basalts, the removal of material from steep slope sections and the successive downcutting due to drainage incision contribute to this variation in form. Examples of the profiles surveyed by Allison and Higgitt (1998) are shown in Figure 2.10.

Figure 2.10 Slope profiles measured in the eastern Badia (after Allison and Higgitt, 1998)



A: Abed basalt; B: Madhala basalt; C: Bishriyya basalt; D: Scouracious materials and remnant volcanic cones

The profiles surveyed by Allison and Higgitt (1998) had their toe positions located in a range of drainage features including wadis, Qa'a and Marab. There was no differentiation between profiles at different points in a drainage network. No work has been undertaken to assess the degree to which drainage development and the position of the slope profile within a drainage network relates to slope form. Slope profile form acts as a critical control on dictating whole slope dynamics. With such a pronounced diversity in profile forms the resulting slope hydrology is likely to be equally diverse. Only with a full understanding of slope form and surface character variation can whole slope profile hydrology be fully understood.

2.4.4 Sediments

Sediments are found in topographic depressions as in-washed deposits underlying the clast dominated slopes. Sediment pans accumulate in topographic lows to where large amounts of mobile sediments are transferred during rain events. The closed depressions result in water loss through evaporation and infiltration. Sedimentation is extensive. The size range of pans is also significant, ranging from the massive Qa'a El Jafr greater than 25 km in diameter, to smaller features, just tens of metres across. Sediments pans are categorized into two distinct morphological types: Qa'a and Marab.

Qa'a are closed topographic depressions where runoff accumulates. Water either evaporates or percolates into the sediment infill, leaving clays and silts in thin laminations. The particle size of surface sediments reduces across Qa'a surfaces. Areas of the Qa'a surface close to slopes or inflowing wadis display more coarse fragments, gradually fining across the feature. Qa'a often display desiccated surfaces. Qa'a sediments exhibit banding of coarse and fine materials. Sediments are highly weathered. Fining up sequences and variations in sediment colour indicate diverse inputs and variable sediment transport mechanisms.

Marab have coarse surface particle sizes, often contain an active channel bed at their base and are laterally constricted by steep sided slopes. Bed-form structures indicate the transport of large amounts of water. Marab also play an important role in the storage of water in the region. Marab contain significant concentrations of zeolite in their sediments (Ibrahim, 1993). Marab frequently display standing water for significant periods of time after rainfall events. Marab surfaces are some of the first places to develop vegetation during the spring months. Sediment infill also contains rock, often of boulder sizes, around which there is considerable scour, demonstrating the massive volumes of velocities of flow and resultant transport capacity when in flood. Marab are regarded as open systems. They freely drain either into wadis normally where a geological constriction forces the adjustment of their course, or they feed into Qa'a features. Marab sediments are very different to Qa'a. Coarse gravels, in addition to sand, silts and clay have pronounced layering in Marab deposits, representing the flashy and extreme nature of Marab flood events (Grove, 2000). There is a distinction in particle size between Marab and Qa'a (Figure 2.11), with a dominance of coarse silts and sands in the Marab.

The occurrence and development of Qa'a and Marab can be related to the age and evolution of the drainage development of the basalt surfaces as seen on the Landsat TM image (Figure 2.8). Qa'a and Marab are found more frequently on the older basalt surfaces. The loosely compacted surfaces of Qa'a and Marab provide a source of aeolian sediment. Surrounding topography channels both water and wind, making both Qa'a and Marab surfaces dynamic zones of sediment supply, transfer and storage.

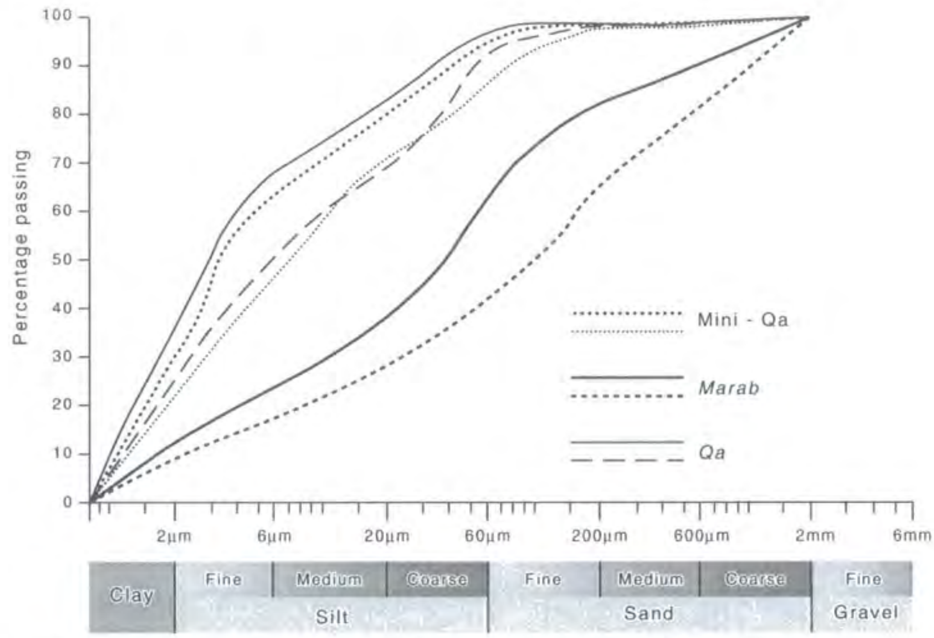


Figure 2.11 Particle size characteristics of Qa'a and Marab features (after Allison *et al.*, 2000)

The presence and nature of slope sediments varies with slope form. The clastic surfaces present significant aerodynamic roughness to windblown sediments. Evidence of intense weathering in the Badia is also apparent. Allison and Higgitt (1998) propose a model of the down-slope variation in sediment depth and surface clasts (Figure 2.12). The model suggests slope crests have little sediment and clasts therefore stand proud of the surface. Sediment depth increases progressively downslope, indicating increased sediment deposition. The downslope nature of the clast configuration on the surface changes, showing increasing clast burial downslope profiles (Higgitt and Allison, 1999b). The Allison and Higgitt (1998) model raises several questions. The increase in depth of sediments has not been quantitatively derived. Plateau areas, which are large expanses that bridge between drainage networks and slope crests, may support significant depths of sediment. Sediment depth is dictated by the presence of swales and hollows across the slopes. The distribution of surface sediments in the field seems more complex than the proposed model. Allison and Higgitt (1998) use the surface configuration of clasts as a relative indicator of sediment transport. The implication is that the nature of sediment dynamics is further complicated by topography and drainage. A systematic spatial sampling framework is needed to generate a clearer understanding of the surfaces and how their form relates to the development of drainage networks.

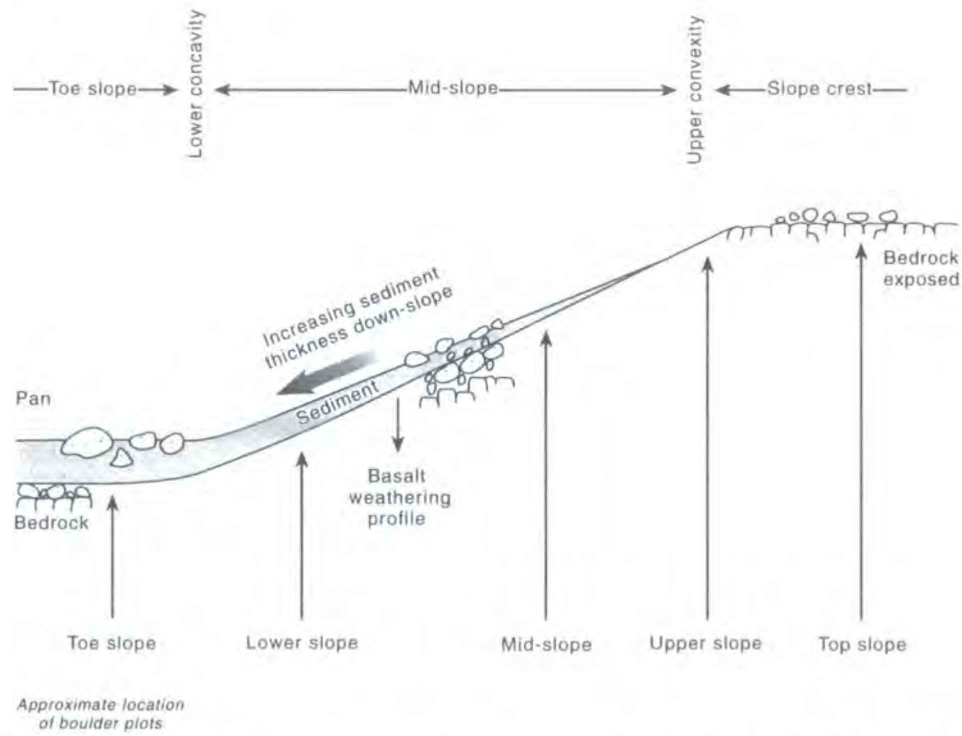


Figure 2.12 Sketch diagram illustrating associations between slope, sediment thickness and the nature of boulder exposure (after: Allison and Higgitt, 1998)

Slope sediments in the northeastern Badia are generally fine grained, with typical size fractions ranging from clay loams to silty clays, with in excess of 50 % clay and 30 % silt (Fisher *et al.*, 1966). The particle size distribution of the sediments has a critical importance on transport and erosion by aeolian and hydraulic action. Clear evidence of pedogenesis is evident in the field. Gypsum is clearly visible deep in the weathering horizon indicating the movement of water. Spherically weathered ghost stones, desiccated bedrock, re-deposition into cracking structures and limited bioturbation are all in evidence. Soil surfaces also show considerable variation. Some exhibit small clasts of basalt or carbonate, forming a continuous cover similar to a desert pavement mosaic (Dixon, 1994). Others have clay fines, sealed and then crusted and cracked (Kirk, 1997). Larger particles, mainly gravels, tend to be focussed around the perimeters of clasts. The presence of a vesicular horizon, similar to that noted by McFadden *et al.* (1998) and Brown and Dunkerely (1996) is present but not continuous across the landscape. Carbonates are present in clast base accretions and also within lenses in the sediments.

Where topography concentrates water, sediments alter. Areas which regularly become inundated or experience overland flow, for example ephemeral pathways between depressions and wadis, show considerably more surface carbonate accretions.

Soils in the northeastern Badia are relatively thin, poorly developed and closely linked to the underlying geology, characteristic of many arid zone soil formations (Morman, 1959, Wieder *et al.,* 1985). Soils and sediments are deep red brown (105YR 4/4-6/6) (Kirk, 1997), though this varies between basalt flows. Soil depths are highly variable and their nature is dependent on slope position, geology, and local relief and the subsequent up-slope contributing areas (Allison and Higgitt, 1998). Soil types are relatively uniform, most of which fall under the Camborthid classification (Table 2.6) (Huntings Technical Services Soil Surveys, 1965).

Soil taxonomic subgroups	Soil description	Colour	Location and geomorphology
Typic Camborthoid	Deep silty-sandy clay loam, compacted at depth with basalt stones and gravel at 0.5m, often with hard capped vesicular surface	7.5-5YR 5/6-4/6 or 10-9YR 5/6	Across the region, beneath basalt rock mantle
Xeretic Camborthid	Heavy silty clay loam to clay. Strong platy to wedge structure but lacking slickensides. Often compacted at depth	7.5-5YR 5/6-4/6	Flat to gently sloping Qa'a features and alluvial plains
Xerochreptic Camborthid	Silty clay loam to silty clay, often with moderate sub-angular blocky structure. Developed from limestone alluvium, becoming sandy and gravely with depth	7.5-10YR 5/6-4/6	Small localised concentrations, but more common on the southern flank of the basalt flows
Typic Calciorthid	Deep very gravely silt loam to sandy clay loam to clay loam. Large soft to moderately hard calcareous concentration producing a calcic horizon from about 0.2m depth. Common manganese concentrations	7.5-5YR 5/6-4/6	Wide wadi beds, marab surfaces, sometimes with caliche
Typic Torriorthent	Unstructured, extremely gravely coarse sand to sandy clay loam, poorly sorted	7.5-5YR 5/6-4/6	Wadi and marab beds in the north of the region

Table 2.6 An overview of soils on the northeastern Jordanian basalt plateau (Huntings Technical Services, 1965)

Present day soils and sediments may not be representative of present soil forming processes in action but may be relics of past climates (Al-Hamoud *et al.,* 1995). Kirk (1998) suggested that the formation of the soils in the northeastern Badia is more complex than was previously thought. The presence of calcareous nodules and the predominance of silt-sized quartz grains in the soil matrix imply exogenous sources of sediment supply to the region (Kirk, 1998). Consideration of aeolian processes, in particular high magnitude events, suggests the likelihood of the influx of aeolian material to the northeastern

Jordanian Badia (Bruins and Yaalon, 1979).

Issues of slope, playa and plateau connectivity can be extended to the cross-contour continuity of slope processes. Swales and hollows and the presence of Qa'a deposits on elevated plateau surfaces tends to concentrate flow in topographic lows on the side slopes of the incised drainage network. The plateau does not drain uniformly into adjacent wadi networks. The dominant form of flow may be concentrated into small flow pathways, rather than sheet flood which flows across the width of a slope. Evidence for the concentration of overland flow into pathways is seen in the spring months, when vegetation grows predominantly on routes of preferential water flow, commonly in very subtle topographic depression. A key question is to what extent do the profiles surveyed represent either an active zone of flow concentration and intense process, or conversely a swale where less intense flow is experienced? Additionally significant microtopography has been observed in the northeastern Badia.

2.4.5 Clastic surfaces

There are significant differences in the character and configuration of the clastic surface cover with geology and slope (Allison *et al.*, 2000). Variations in the mean intermediate axis between locations show distinct differences in surface character between basalt types. The oldest flows, the Abed, have a mean intermediate axis dimension of 0.16 m, compared to 0.105 m on the younger Scoriaceous deposits. Variation in surface cover relates to jointing structures of the basalt, as a control on the nature of weathering, rather than a temporal change (Allison and Higgitt, 1998). Abed basalts have a larger mean surface area (0.32 ± 0.08 m2) and greater edge lengths (0.66 ± 0.11 m) than any of the other basalts studied. The degree of sorting, shown by use of the coefficient of variation and the clast size distribution characteristics also varies between basalts (Table 2.7).

Basalt	Mean skewness	Standard deviation (skewness)	Mean Cv_b	Standard deviation (Cv_b)
Abed	0.71	0.80	34.83	5.88
Bishriyya	1.41	0.50	37.81	10.99
Madhala	1.07	0.62	36.83	6.61
Scoriaceous	1.52	0.58	43.97	19.93
Cleared	1.11	0.59	43.97	6.61

Table 2.7 Clast size distribution parameters and sorting by basalt type (after Allison and Higgitt, 1998b)

The oldest Abed surfaces exhibit clast size distributions with the lowest levels of skewness (0.71) when compared to the Scoriaceous surfaces (1.51). The preferential removal of smaller clasts either hydraulically or through weathering on the older slopes is thought to account for the depletion of the tail of the distribution. The results presented by Allison and Higgitt (1998) show a preferential sorting on the older slopes, with fewer smaller clasts in the distribution. Attempts to gain a precise measure of percentage rock fragment coverage from clast axis dimensions have included the use of an elliptical function to derive the surface area of each individual clast, rather than calculations based on mean clast sizes (Higgitt and Allison, 1999a). This technique is successful, as clear differences in surface character are noted between basalt types (Table 2.8). This degree of surface cover variation is also reflected in remote sensing imagery, whereby the spectral reflectance of each basalt flow surface has a unique signature which can be used to delimit the flow extent (Tansey, 1999).

Basalt	Mean Ground Cover (%)	Standard deviation
Abed	50.77	14.27
Bishriyya	46.44	21.71
Madhala	39.61	15.30
Scoriaceous	19.68	13.11

Table 2.8 Ground coverage by basalt type (from Higgitt and Allison, 1998b)

Systematic variation of surface character within individual basalts and down slope profiles has been studied (Allison and Higgitt, 1998). Links with slope form are less clear than those identified between geologies. Data presented by Allison and Higgitt (1998), when aggregated by basalt type, present systematically varying patterns of surface cover with distance downslope. On the Bishriyya and Scoracious deposits, the intermediate diameter is at its highest at the upper and middle slope plots, which then reduces consistently downslope. The Abed flows show a continual rise in clast size towards the lower slope position, while the Madhala slopes show little discernable spatial differentiation in surface character. It is suggested that slope form controls clast surface character, which leads to a temporal variation as slope form evolves (Higgitt and Allison, 1998; Allison and Higgitt, 1998). The locus of maximum slope coincides with the largest mean intermediate clast axis dimensions. Slope gradient and skewness are not significantly related, limiting the application of the suggestion that there is a preferential removal of finer clasts on steeper slopes.

A clear decline in percentage ground surface cover is apparent downslope (Allison and Higgitt, 1998). The younger Bishriyya and Scoracious slopes show a peak ground surface coverage at the upper slope position, whilst the surfaces of the Abed and Madhala display a steady decline in ground cover downslope. There are differences between toe and crest positions, explained by the location of the toe plot either in or on the boundary of the adjoining wadi, Marab or Qa'a (Allison *et al.*, 2000). Little or no ground cover is not unusual at slope profile toe sites, attributed to the deposition of slope sediments and intense periodic fluvial scour.

Clast exposure above the slope sediments reduces downslope (Higgitt and Allison, 1999b). Consistent variations in clast burial are also noted on the variable slope forms between geologies (Higgitt and Allison, 1999). Statistically significant univariate correlations are found between exposure and slope length, height, curvature, shape, but not gradient (Table 2.9).

Slope position	Mean ground cover (%)	Standard deviation	Mean exposure (%)	Standard deviation
Crest	42.9	17.1	69.5	11.7
Upper	48.1	14.9	65.6	10.7
Middle	40.9	16.1	58.2	11.9
Lower	38.7	18.4	55.8	12.5
Toe	16.9	9.0	37.4	6.5

Table 2.9 Influence of slope position on ground surface configuration (after Higgitt and Allison, 1999a)

Data previously presented appears to show a downslope link between clast exposure and profile shape. Clast exposure indicates the degree to which sediments are mobilised and redeposited further downslope (Higgitt and Allison, 1999b).

2.4.6 Evidence of process action in the northeastern Badia

There is much evidence in the field to suggest the nature of processes that are responsible for the nature of surface processes and geomorphic change. Two studies have been undertaken into direct process action in the northeastern Badia. Kirk (1997) examined the role of rainfall in acting to promote soil crust development, and Warburton (1998) conducted a pilot study into the variable rates of infiltration on various sediment surfaces across the region. Infiltration is highly variable and sporadic (Warburton, 1998). With sparse and erratic rainfall, runoff and ephemeral flow is short lived and irregular. Infiltration into channel alluvium and the desert surfaces is highly variable, a feature common to such desert surfaces (Warburton, 1998; Agnew and Anderson, 1992). Wadi flows have not been quantified, but the displacement and removal of massive boulders, up to 1 m in diameter, has been observed. Trim lines on the slopes surrounding wadi beds also indicate high levels of flow in the wadi channels. Surface runoff has been reduced in recent years due to the construction of dams and the use of surface water for irrigation in the head waters. A reservoir was constructed in Jordan, across Wadi Rajil in 1980 but this is known to have only filled twice in between its emplacement and 1998 (Dottridge, 1998). Rainfall simulation experiments undertaken in the region on agricultural land by Kirk (1997) indicate the importance of surface rock fragments on controlling infiltration, surface seal development and the rapid speed of run off generation.

An intuitive assessment of the dynamics of the northeastern Badia might imply an inert and inactive environment. Heavily varnished clasts, low levels of water and moisture, and the sporadic and infrequent occurrence of flood or storm events suggest a dormant environment. A more detailed examination of the geomorphology has revealed a greater degree of surface clast sorting with slope, a systematic variation of slope form with age, heavily incised wadi networks and massive accumulations of redeposited weathered material, indicating a greater level of geomorphic activity, either at present or in the past.

The nature of events that are responsible for the features described remains unknown. Large volumes of overland flow would be expected to initiate rill and gully development (Horton, 1945). Scour and deformation of the sediments maybe expected around surface clasts (Bunte and Poesen, 1993). A greater differentiation between slope sediment source, transport and deposition zones might be expected (Yair, 1990). None of the features is continually apparent or prevalent in the northeastern Badia.

Taking surface hydrology as the most influential process (Allison and Higgitt, 1998), formative events maybe characterised into two broad groups. First, low-magnitude high-frequency rainfall, and second, high-magnitude low-frequency storm-events (Kirk, 1997). The relative geomorphological influence of the two types of event is not understood in the northeastern Badia, nor is the clarity of the distinction between them. Previous research elsewhere upon the influence of surface clasts on slope hydrology has noted both a positive (Abrahams and Parsons, 1991; Valentin and Casanave, 1992; Brakensiek and Rawls, 1994) and a negative influence (Hinckley, 1980; Brackensiek and Rawls, 1994). Positive (van Asch, 1980; Wilcox *et al.*, 1988; Poesen and Inglemo-Sanchez, 1992) and negative effects (Box, 1981; Collinet and Valentin, 1984; Simanton *et al.*, 1984) on sediment dynamics have also been recorded. The slopes of the northeast Badia are indicative of a predominantly negative series of feedbacks between surface form and process. High concentrations of slope sediments suggest a negative feedback which acts to restrict the erosion and removal of the slope sediments. The lack of geomorphological evidence of high magnitude events on the slopes suggests that their formative influence is muted by the clast cover.

Evidence is available in the field which suggests the nature of surface modification (Allison *et al.*, 2000). A preferential sorting of the clast population to the base of the slopes indicates the removal of the smaller clasts of the population, probably by the hydraulic action of overland flow. Second, a non-random, often structured distribution of the clasts on the surface has also been noted. Surface clasts must have moved to form these structures, as there is no other logical explanation for this structured positioning. Allison and Higgitt (1998) used surface clasts as a relative measure of sediment transport but this does not explain the spatial organization of the surfaces. If a close link between process and form is assumed, an iterative mechanism of clast movement is favoured. An iterative mechanism of surface modification is supported by the modification or muting of process action by the surface configuration. Clasts are relatively massive objects which cannot be mobilised through direct transport by flow (Poesen, 1987). With significant climatic change and the ages of the surface, what today is considered a large scale event may only be a small scale event in the geomorphological history of the surface evolution.

The nature of the surface cover character has been previously shown to vary in several ways down slope profiles. The shape of individual clasts and the nature of the whole ground surface cover changes (Higgitt and Allison, 1999a). Field observation has also noted the presence of a distinctly non-random distribution of surface clasts (Higgitt and Allison, 1999a). Several mechanisms of movement can be suggested which have resulted in the downslope variation observed. The iterative movement of clasts can be suggested to be based upon the downslope settling or toppling of clasts after a small scale vertical disturbance or displacement. Although hydraulic action may not be of sufficient magnitude to entrain movement, it may be sufficient to instigate clast instability, through for example runoff creep (Abrahams *et al.*, 1994). Several studies have identified the interaction between a deformable sediment surface clasts or obstacles, such as clasts (Bunte and Poesen, 1994; Schitling, 1955). Scour around the clast perimeter in a similar manner may lead to undercutting, which in turn may destabilise a clast, promoting the clast to subside into the resulting scour hole.

With gravity, the preferential re-settling direction of clasts will be downslope. The product of multiple iterative movements is the down-slope migration of clasts. Several potential geomorphic mechanisms for a mechanism of instigating an iterative movement in the northeastern Badia are evident. First, analysis of the slope sediments in the Badia shows high levels of clays and silts (Allison *et al.*, 2000). The expansion and contraction of the clays with wetting may promote vertical displacement of clasts (Springer, 1958). In this instance low-magnitude events which wet the surface but do not generate overland flow may have a significant geomorphic effect in acting to displace surface clasts, through surface saturation. Second, significant levels of carbonate accretion have been noted on the undersides of surface clasts (Plate 2.3). The preferential precipitation of carbonates beneath clasts may again prompt an iterative vertical displacement of clasts, though no empirical evidence of this is available.

Plate 2.3 Carbonate accretions on the undersides of basalt clasts

Very low ground surface temperatures and the relatively high levels of moisture in the surface sediments during the winter may prompt ice needle growth beneath clasts, again instigating a slight vertical displacement. Direct testing of these mechanisms in the field is difficult due their scale of action.

2.5 Conclusion

The northeastern Badia represents a diverse and dynamic environment. The interplay of climate and geology has resulted in a unique and complex geomorphology. Previous work has identified significant links between slope form and ground surface cover, pointing tentatively towards slope hydrology as the key formative influence on surface configuration. The actual process mechanisms of surface dynamics and clast movements are less clear, but field observations suggest iterative changes over a long time period.

Location and the influence of drainage patterns and basalt type influence slope form. The linkage between geological age and slope form is less clear and has been based on a limited sample both in terms of spatial and statistical significance. Several questions arise which need to be addressed if this landscape is to be understood in greater depth and allow links between form and process to be explored.

The nature of the geological control on surface character has been previously studied, raising issues of scale, sampling adequacy and what constitutes an appropriate measure of surface. The subtlety of variation in surface character is clear but a significant degree of local scale heterogeneity, or noise, is apparent which cannot easily be accounted for. The degree to which this variability can be linked to slope or geological controls needs to be addressed. The varying degree of drainage development, the age of the surfaces and the variation in slope profile form are all controls on surface character but their relative influence and importance is not well understood. There is a requirement for a precise and detailed study of surface geomorphology. The study should be undertaken in a manner which accounts for the subtlety of variation in surface form in the northeastern Badia. The study should derive measures of the surface which are appropriate to the processes which act to modify the surfaces.

Chapter 3: Site selection, description and sampling

Chapter 3: Site selection, description and sampling

3.1 Introduction

The main objective of this chapter is to select and describe the sample sites used within this study. There are three sets of issues that relate to sample site selection. First, scale, location and adequacy of sites in the context of the whole northeastern Badia, second, an appropriate scaled framework for data collection, and third, the specific locations for data collection and their geomorphological characteristics.

The approach developed in this thesis is based a hypothesis of surface dynamics which is developed on three key considerations which have come to light in a review of research previously undertaken in the Badia. First, scale appears to be of critical importance, both in terms of surface variability, process action and the scale of investigation. A nested hierarchy is developed as a framework within which semi-quantitative links between scale boundaries can be considered. The scaled approach aims to strike a balance between the fine scale precision necessary to detect the systematic surface variability, against a sample size which is large enough to be statistically and spatially significant. Second, location relative to both geology and drainage development appears to have a profound influence on the ground surface configuration. Low level aerial imagery reveals a complex mosaic of ground surface coverage, dictated by microtopographic variations and the presence of bedrock exposures. A systematic method of positioning a sample site is necessary, such that site location can be considered in the context of the larger natural system. If a sample location can be definitely known not to be atypical then comparisons can be drawn between sites in similar situations with confidence. Finally, the approach of the study must be appropriate to both the nature of geomorphological processes in the northeastern Badia and the objective of the study. Change is very subtle and the surface appears to be highly complex. Measurement of relevant aspects of surface form and behaviour is essential.

Given the subtle levels of variability in surface coverage, the sporadic and subtle nature of surface modification, direct observation of process is difficult. The sampling technique developed here aims to locate sites which can be considered statistically within the context of the wider geomorphological system. The location for both surface characterisation and experiments on surface hydrology is suggested to have a significant influence over the results generated, and therefore must be selected carefully.

3.2 Methodological considerations

3.2.1 Introduction

Scale, location and adequacy have been widely discussed elsewhere (Schumm, 1991; Dunkerley, 1994; Blöschl, and Sivapalan, 1995). A comprehensive review of each is beyond the scope of this research. Studies concerned with coarse clastic surfaces (Poesen *et al.*, 1990, semi-arid slope hydrology (Parsons and Abrahams, 1992) and clast surface modeling (Ahnert, 1994) provide reviews of a range of work which has in part addressed issues of scale, location and adequacy. Previous work is used as the basis for the construction of an appropriate methodology for the research presented in this thesis.

3.2.2 Scale

The importance of scale in the northeastern Badia can be explained by use of an example. Variation in clast surface configuration occurs between plot positions at various points down a slope profile. Surface configuration varies systematically with slope form and geology. Variation in surface character is measured as small changes in the mean character of a number of clasts in a sample from a series of plots. Additionally, minute variations are apparent between clasts within each sample at each plot location. This local variation, or heterogeneity, is of a similar magnitude to the systematic downslope variation in surface character. In the northeastern Badia the scale of variation in surface character is commonly not of the same scale at which the surfaces are easily characterised. Very small changes in mean surface character are only apparent between disparate locations. Understanding the scales at which variability occurs, the scale at which the surfaces can be characterised and linking between these scales is important.

The consideration of scale falls into three broad categories. The scale of variation in the landscape form; the scale of process action; and the scale of investigation. The scale(s) at which the surfaces are studied is ultimately a balance between the precision of measurement against the size of the sample taken. Ideally all surface clasts would be measured in an infinite level of detail.

The features of the landscape warrant subdivision into a series of scale boundaries, defined by the nature of variability in landforms, the logistical constraints of investigation and adequacy of the sample collected. This is used to examine the interactions between various components of the landscape. As a framework for examining the scale of form variation and the scale of process variation, a nested hierarchy of scales has been developed (Figure 3.1). The hierarchy is based upon the hypothetical scale boundaries proposed by Blöschl and Sivapalan (1995) and Poesen *et al.* (1994) and is applied to the specific context of the northeastern Badia. A discussion of each of the scale divisions describes the scale boundaries and the dominant controls on the geomorphology of the northeastern Badia in this framework.

i Regional scale

At the regional scale the northeastern Badia is considered within the context of the climate and structural geology. The climate of the northeastern Badia is linked with continental scale meteorology, which is dominated by the transition between the Mediterranean and arid interior climates of the Levant. The large-scale topographic features of the Arava Rift and Jebel Druz are highly influential. The structural geology has been shown to dictate the location of various rock types in the region. Combined with climate, the relative position of sedimentary and igneous deposits influences the location of aeolian sediment supplies and potential zones of dust accretion, respectively.

ii Catchment scale

At the catchment scale the importance of basalt type and drainage development influences the configuration of slope form and surface character. Additionally it has been suggested that drainage evolution is related to basalt age and mineralogy and may hence dictate slope form (Higgitt and Allison, 1999a). Additionally, local topographic controls on climate have been noted, including the tendency of dust devils to form over reflective Qa'a surfaces, and the channelling of winds in the wadi networks.

iii Slope profile scale

At the slope profile scale, mean variations in ground surface cover are significant, suggesting the influence of variable slope process action. It is suggested that only by understanding variation in surface form at the slope profile scale can an understanding of the landscape be gained (Allison and Higgitt, 1998). Process has been suggested to vary in a similar manner to the variation in surface form down slope profiles.

iv Plot scale

The plot scale is in effect the scale of investigation; surface characterisation and field experiments on surface hydrology are logistically constrained to this scale. Local heterogeneity is of importance and it is here that a balance between sample size and the precision of the measurement technique must be sought.

v Subplot scale

The subplot scale, on a surface with such subtle variability in form, is potentially the most significant in terms of dictating variations in process response. Variations in interactions between the surface clasts, the underlying sediments and any slope processes at the subplot scale may result in variability at higher scales.

The scale boundaries described are not exclusive and their boundaries are by no means fixed. The hierarchy provides a useful framework within which the various components of the landscape and their interactions can be understood. Process at one scale may have a profound influence on the character of another scale. An example of this is the concept of emergence, whereby the cumulative action of process at one scale results in features or properties at a higher level which are not discernable from the character of the individual components at the smaller scale. Interdependence between scales works both up and down the hierarchy. For example, Allison and Higgitt (1998) have shown that whole slope profile form influences local ground surface configuration. The systematic variation in ground surface cover may also influence the whole slope hydrology. Each of the scales identified has a specific link to the geomorphology of the northeastern Badia, which broadly defines a scale of variation in the landscape geomorphology.

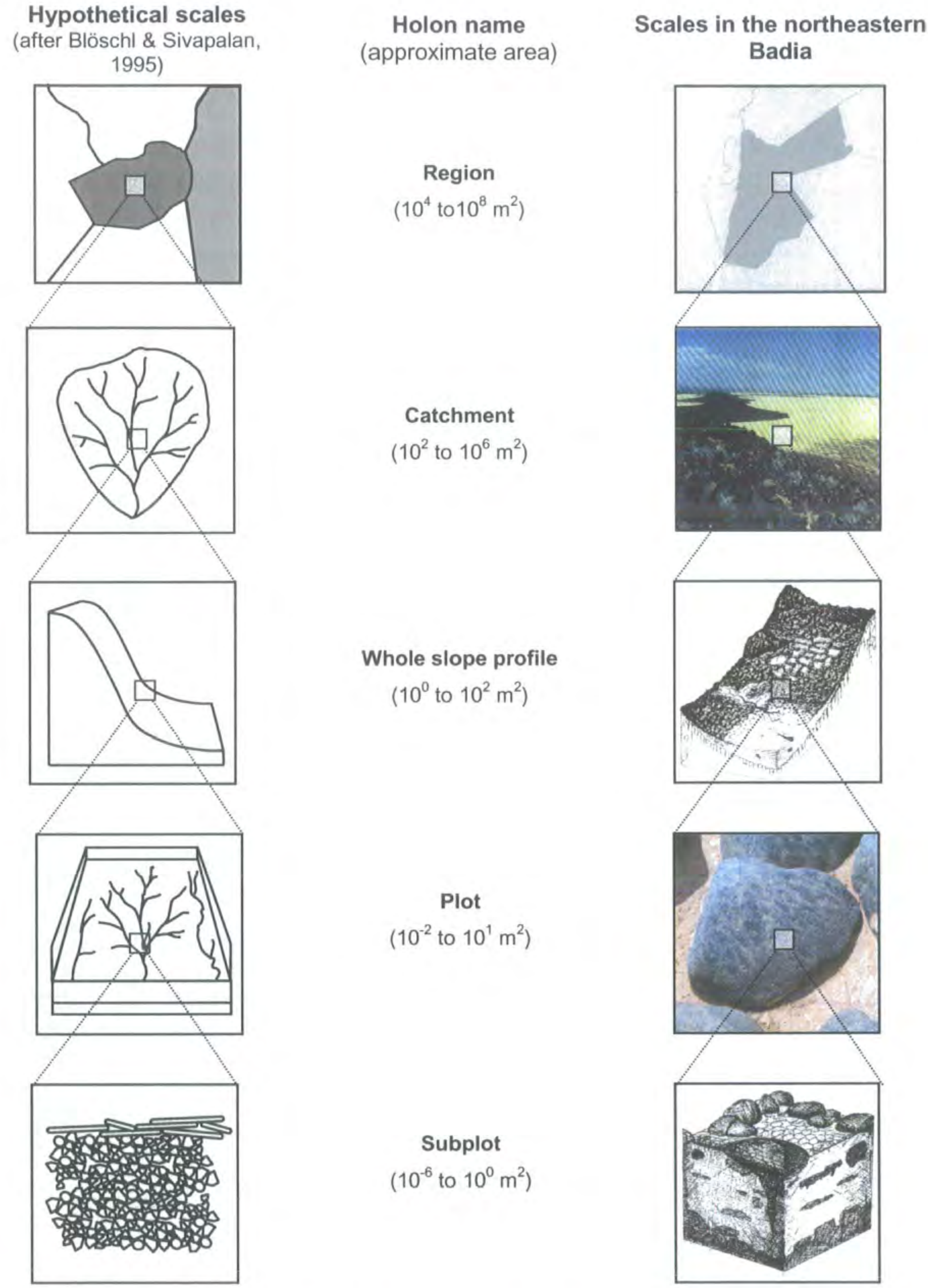


Figure 3.1 Scale boundaries, theoretical and applied to the northeastern Badia

Several studies have adopted a hierarchy of scales to extrapolate and up-scale results (Kirkby *et al.*, 1996). Two factors restrict the validity of extrapolation between scales when applied to the northeastern Badia. First, up or down scaling must account for the degree of variability in character at each scale on the surface in question. For example, the degree of variability in clast size at a scale maybe more significant than a mean size as a control on surface hydrology (Dunkerley, 1996). Second, is the issue of linking two dimensional measures of geomorphology to a three dimensional understanding of landscape. Slope profiling, for example, is commonly employed to gain an understanding of the distribution of slope forms in a given landscape. The relationship between the numbers of profiles necessary to gain a robust approximation of the three-dimensional character of a landscape is not clear given the apparently arbitrary profile location commonly used. Profile location is of particular importance where drainage development influences slope form. The validity of extrapolating two dimensional data to a three dimensional understanding of landscape is questionable and should only be undertaken with caution. Finally, there is the issue of emergence. A reductionist study at the plot scale may not reveal emergent properties at higher echelons in the scale hierarchy. Given the apparent complexity on the surfaces of the northeastern Badia some consideration of this effect is necessary.

Scale of investigation applies to both surface characterisation and surface hydrology. In terms of surface hydrology, this is a balance between local scale variability, which in semi-arid environments is generally high (Agnew and Anderson, 1992), and the logistical constraints of plot size. No previous work on surface hydrology has been undertaken on the clast mantled slopes of the northeastern Badia. Basing a sampling framework on a theoretical degree of variability in surface hydrology is dangerous. Instead, it is suggested that a close link between surface form to surface process exists, as is suggested in the northeastern Badia by Higgitt and Allison (1999). A considerable volume of work is available to support the link between clastic surface configuration and the processes in action on that surface (Poesen and Lavee, 1994). The assumption that process response will vary in a similar manner and with a similar degree of variability as surface form appears sensible. The scale of investigation for this study is based on the findings of the previous work on surface form variation. As a more detailed example, surface characterisation provides a basis on which to define the scale of investigation. Given the previous volume of work conducted in the Badia an estimate of an appropriate scale of investigation can be made.

There is no standard method of assessing or characterising coarse clastic surfaces, but it has received much attention. A wealth of literature is available on appropriate sample size needed to gain a statistically significant understanding of coarse clastic surfaces (Diplas & Fripp, 1991; Wolcott & Church, 1991; Gale & Hoare, 1992; Dunkerley, 1994). The result is a disparity in methods and approaches adopted, with no apparent consistency. Table 3.1 summarises the approach from twelve studies of coarse clastic surfaces. There is both a disparity in the sample number considered to be adequate to gain statistical significance, the way in which the sample site is located and the measurements taken.

Author	Sample size	Sample area and location	Measurement type
Perez (1986)	25 > 25mm	5cm x 5cm	ucam
Cooke and Reeves (1976)	50 > 5mm	50.8mm x 50.8mm	ucam
McFadden *et al.* (1987)	50 > 8mm	-	ucam
Abrahams *et al.* (1988)	200	Grid based sample	ucam
Abrahams and Parsons (1991)	56 – 70 > 2mm	Grid intersection sample selection	ucam
Abrahams *et al.* (1995)	50 – 200, > 2mm diameter at grid intersections	5cm x 10cm (long axis down-slope)	ucam
Allison & Higgitt (1998)	All clasts in 4m2 quadrat Mean = 67.8	2m x 2m, regularly spaced relative to slope	All exposed dimensions
Brown & Dunkerley (1996)	50	6 plots evenly spaced down-slope	Mean diameter
Al Farraj and Harvey, (2000)			Semi-qualitative / quantitative
Friend *et al.* (2000)			Stratified random sample
Box (1981)	Photograph projected on a grid to calculate cover percentage – sieving to calculate size distributions.		Stone weight per unit area, in seven sieve units.
Nyssen *et al.* (2002)	Grid node count of rocks in quadrat	1 – 1.2 m^2plot	Uncorrected median intermediate diameter

ucam: – uncorrected arithmetic mean intermediate axis

Table 3.1 Examples of coarse clastic surface measures employed in characterization

Blöcshl and Sivapalan (1995) provide an intuitive understanding of the balance between process and observation scales (Figure 3.2). If the process, or feature, under observation is larger than the extent of the sample frame then this will appear as a trend. Conversely, if the process is smaller than the resolution of the observation, then it will appear as noise in the data. To overcome this Russo and Jury (1987) suggest an adaptation of the Nyquist frequency, developed for assessing the highest frequency (fn) that can be detected in a given data set of spacing (d) (Equation 3.1).

Eq. 3.1

$$f_n = \frac{1}{2d}$$

Applied to the northeastern Badia, the wavelength of spacing of regular microtopography dictates an appropriate scale of sample size. A sample should be of a size or extent which is significant both statistically to calculate clast size population and spatially such the heterogeneity or structure can be understood.

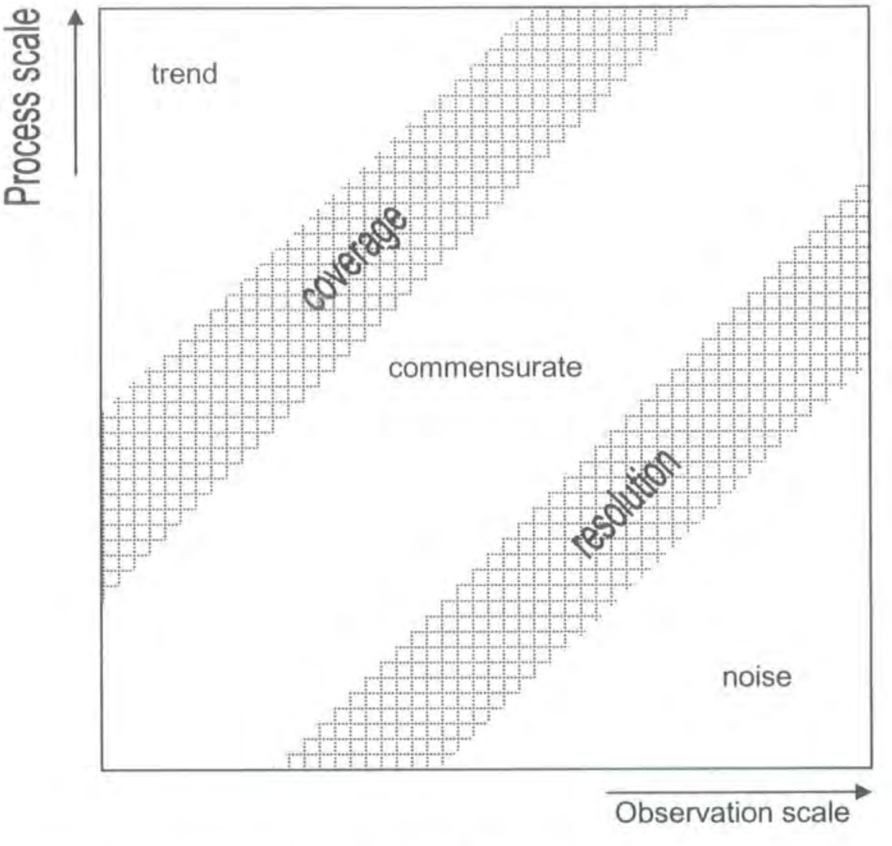


Figure 3.2 Process scale versus observation scale (after Bloschl and Sivapalan, 1995)

The scaled approach developed above is used as the basis for this investigation. Specific scales of variation and scales of investigation are discussed further in the design of the surface characterization and the surface hydrology experiments in Chapters 4 and 5.

3.2.3 Location

Location and scale in the northeastern Badia are closely related. The importance of location is best explained by means of an example. A square plot is randomly positioned in the northeastern Badia. Within this quadrat the character of the ground surface cover is influenced by the position of the plot relative to the whole slope profile and the nature of the underlying geology. The issue of location is, therefore, how representative of the landscape or area as a whole is that plot on that profile? A link between slope form and drainage, and geology and drainage development has been suggested (Allison *et al.*, 2000). Controls on the geomorphology are dictated by the location and relative position of each other and therefore cannot be considered independent. Any selected profile is likely to be only one slope form in a spectrum of slope forms on one basalt type.

There appears to be a complex interaction between slope, geology, drainage and age is suggested. Slope form has been linked to basalt age (Allison and Higgitt, 1998). The variation in slope form may merely be a reflection of different states of drainage evolution with basalt age. The variation or range of slope forms within a single geology and the reasons for this variation has not as yet been assessed. Given the transition of slope form with catchment and drainage development, it would be expected that profile form may vary accordingly (Selby, 1993). Allison and Higgitt (1998) developed a systematic method of locating plots relative to a whole slope profile but no robust method of locating profiles within a drainage system or region has been developed. A standard profile form was assumed to be characteristic of each basalt, so profile position or location within a single basalt flow was not considered important. The ease with which the results from one place can be extrapolated to another depends on how similar they are, or moreover how well the difference in controlling factors is understood.

Location is a simple concept but one that appears commonly overlooked when positioning plots. Standardized plot based studies can easily be undertaken but, the importance of location relative to the larger landscape system is rarely considered. The northeastern Badia provides an extreme circumstance, given the geological and temporal nature of the environment, but emphasizes the importance of considering relative location. Given the importance of basalt type and age and therefore drainage development, a systematic or quantitative method of positioning a profile in a given drainage location is required. Several methods of defining profile location have been proposed (Pitty, 1969) but none has been used to develop a quantitative method of using two dimensional profile forms to assess three dimensional landscape character. A method is developed below using Young's (1961) division of landscape in combination with a GPS derived DEM of the selected field area in the Badia. The method allows a systematic slope profile selection and hence profiles can be considered in the context of the wider system.

3.2.4 Adequacy

Dunkerley (1994) discusses the use of appropriate sampling measures, which he termed adequacy. The character of coarse mantled desert surfaces may be partly relict slope forms of a previous environment (Dohrenwend, 1994). Nonetheless, slope surface character is seen to vary systematically with position relative to the hillslope, irrespective of whether the slope is a relict feature or indicative of contemporary slope process (Dunkerley, 1995). Spatially varying surface cover influences many aspects of slope hydrology and sediment dynamics (Poesen *et al.*, 1994) (Table 3.2). Coarse clastic surfaces present a complex geomorphic system. The influence of surface clasts on slope process is multifaceted but nonetheless a close, albeit complex link between surface form and process is suggested. The implication is that any description or characterisation of the stone surface must be sensitive to both the spatial variability in the attributes of the surface which affect the action of formative processes. With a lack of previous research in the region and on similar surfaces, determination of what is adequate must be based on a hypothesis of surface dynamics. A consideration of adequacy in the research design is necessary to ensure that the components of the investigation are both complementary and appropriate to the context of the northeastern Badia.

It is expected that the clast cover on the northeastern Badia surfaces has many if not all of the influences of rock fragments on slope hydrology found elsewhere (Table 3.2). A further complication is the feedback between form and process. Only a few examples of research exist whereby the relationship between process and form is considered to be homeostatic (Higgitt and Allison, 1999a). The subtle nature of variability, the apparently sporadic nature of formative events and the longevity of the surfaces in the northeastern Badia adds further complication. Adequate sampling and characterisation will yield results with greater significance and application. The importance of adequate sampling applies not only to the characterisation of the form variability of the surfaces but also to any assessment of process variability.

Influential factor	Author(s)	Direct influence
Clast size	Poesen (1987)	Transport thresholds during concentrated overland flow
	Yair and Lavee (1979); Lavee & Poesen (1994)	Nature of rainfall partitioning
Surface area coverage	Abrahams and Parsons (1994)	Surface hydraulics
	Larmuth (1978)	Radiation balance and surface temperature
	Poesen *et al.* (1990); Valentin (1994)	Armouring of surface to raindrop impact
Geometry of clast arrangement	Dunkerley *et al.* (2001)	Effectiveness of laminar flow across the surface Ponding
	Jean *et al.* (2000)	Run off generation
Nature of perimeter contact between rock and sediment	Brakensiek and Rawls (1994)	
	Valentin (1994) Poesen & Ingelmo-Sanchez (1992)	Controls infiltration
Clast character	El Boushi and Davis (1969)	Depression storage
	Childs and Flint (1990)	Absorption
Surface roughness	Goossens (1994)	Aerodynamic roughness
	Darboux *et al.* (2002)	Ponding

Table 3.2 Studies of the influence of coarse clastic material on slope process

Dunkerley (1994) argues that adequacy goes beyond statistical significance. Numerous authors have addressed issues of sampling and associated significance in coarse clastic materials (Kellerhals and Bray, 1971; Hey and Thorne, 1986; Church *et al.*, 1987; Diplas and Fripp, 1992; Gale and Hoare, 1992). Much of the previous work is devoted to statistically significant methods of deriving the full particle size distribution, such that comparative measures, for example the d_{84}, can be derived. The development of 'rules' for sample size, as suggested by, for example, Gal and Hoare (1992), are commonly inapplicable to many real-world situations. The majority of methods of grain size analysis available are tailored to a full clast size distribution description. The levels of detail are commonly not required, nor essential for the purposes of investigation (Dunkerley, 1994). Adherence to methods devoted to gaining statistical adequacy alone does not ensure that meaningful results will be obtained (Dunkerley, 1994). Adequacy is linked to the purpose of the investigation, in addition to statistical considerations. Given the range of research questions posed in this thesis, a number of criteria of sampling adequacy may be necessary.

A second component of adequacy is the degree to which a sample represents the material from which it was taken. Consideration is not only given to the statistical elements but also the geomorphic and sedimentologic character. A method of classification should be able to discern between the variable influence of processes. The choice of characterisation must be guided by an understanding, or hypothesis of, the dominant controls on the condition of the material. Geometric or geomorphic character of the sediment may therefore be just as important as standard size distributions. These considerations have long been discussed in sedimentology (Billi and Paris, 1992).

A final construct of adequacy addressed by Dunkerley (1994) is the applicability of the resulting data to the research questions. Dunkerley (1994) cites the example of describing a rock fragment surface using a single cover percentage in studies of surface hydrology, an approach which is commonly adopted (Poesen & Lavee, 1994). A surface comprised of only small clasts giving a certain percentage cover will have a very different hydrological response to one that has an equal cover but is comprised of fewer, larger clasts. Perimeter length may be of more relevance in this instance as an indicator of surface character relative to slope hydrology and may indeed perform better in statistical analysis.

3.3 Site selection

3.3.1 Introduction

A nested sample site selection approach was developed for the Badia. The scale hierarchy is based on a range of remote sensing, field surveying and field experiment data. Quantitative and qualitative links between scale holons are made such that the location of the field sites can be considered in the context of the wider natural system. The hierarchy is based at five spatial scales. A qualitative assessment of a regional DEM and satellite imagery is made. A local DEM is constructed in the field from which a large number of slope profiles are systematically extracted. Analysis of slope form variation gives an assessment of the variability of slope forms at the field site, from which representative sample site locations are selected. Detailed aerial imagery and DEMs are used in combination to assess the influence of microtopography. Atypical microtopography and atypical ground cover can be identified and sites repositioned.

The sites selected in this research are designed to test within and between basalt variations in surface form and process. The first objective is to assess the variation of surface character and process within one basalt type. This encompasses variation in surface character on five slopes, three of which are quantitatively located such that their profile form can be considered within the context of the whole lava flow. Two further slopes are selected randomly for comparison. A second set of profiles are selected on two other basalts, the Madhala and the Bishriyya. This is used for comparison between basalt types. The method developed is relatively rapid so a total of seven sites, each with five sample points were assessed. Five sites are located in one basalt type, the Abed, to assess the variation of surface character variation within one basalt type. Two further sites are located on Bishriyya and Madhala basalts for comparison. This allows between basalt comparisons. There is need to link surface character to surface process. To achieve this, a series of 27 rainfall simulation experiments are undertaken to assess both local heterogeneity and variability in surface hydrology at nine locations on three slope profiles. The influence of slope form and surface character on surface process can be examined.

3.3.2 Regional scale

The largest scale of sample site selection is based on two factors. A qualitative assessment of site location is achieved through a visual assessment of a regional digital elevation model (DEM), based on 1:50000 map data, held as part of the JBRDP GIS archive, and LandSat Thematic Mapper image (Huntings Technical Services, 1992). The LandSat TM imagery illustrates the proximity of the sites relative to topographic features and drainage networks. An overlay of sedimentary deposits illustrates the location of Qa'a and Marab. After a field reconnaissance to identify potential field sites, the DEM was used to assess the suitability of the location of each, considering ground disturbance, geology, access, location of sites relative to drainage features or sediment deposits and the location of previous research. Using these approaches three field areas were considered. One, Marab Swayed, was selected as the main focus for the study, with the remaining two sites at or near Qa'a al Buqei'wiya acting to act as comparisons between geologies. An example of the LandSat imagery (Figure 3.3) shows the distinction between basalt types as determined by variations in spectral reflectance. A variable degree of drainage development can be seen between basalt flows. Some basalts exhibit greater definition in wadi networks, whereas others show a higher concentration of sediment deposits. The Abed basalts were chosen as the primary location for this study for several reasons. Drainage is well developed, and hence a variety of slope forms are apparent as dictated by incision. The basalt also exhibits an open and diverse clast matrix between locations so variations in form and process should be relatively clear.

The two areas used within this study have been previously selected as key type sites in the Badia (Allison *et al.*, 1998). The sites are found to be qualitatively good examples of their kind, showing a minimal degree of anthropogenic disruption of the ground surface. By using the sites in this study, the value of comparisons between the findings of this thesis and the previous research is enhanced. The sites exhibit three basalt types and a range of drainage features, including Qa'a, Marab and incised wadi networks.

(Bands 7, 4, 2; path 173, Row 32.12N, Date 29.03.92; Huntings Technical Services)

Figure 3.3 LandSat TM imagery – Marab Swayed

3.3.3 Catchment scale

The second stage of site selection is based on a highly accurate DEM of the selected field area at Marab Swayed. The DEM is used to identify slope profile location through a quantitative assessment of slope form variation within a region of the catchment. It is at this scale that a quantitative link is required between slope form and location given the direct link between form and process. An area of Marab Swayed was selected to examine the influence of various slope forms within one basalt type and covered a reach which marked a transition between the wadi network and the Marab deposits (Figure 3.4).

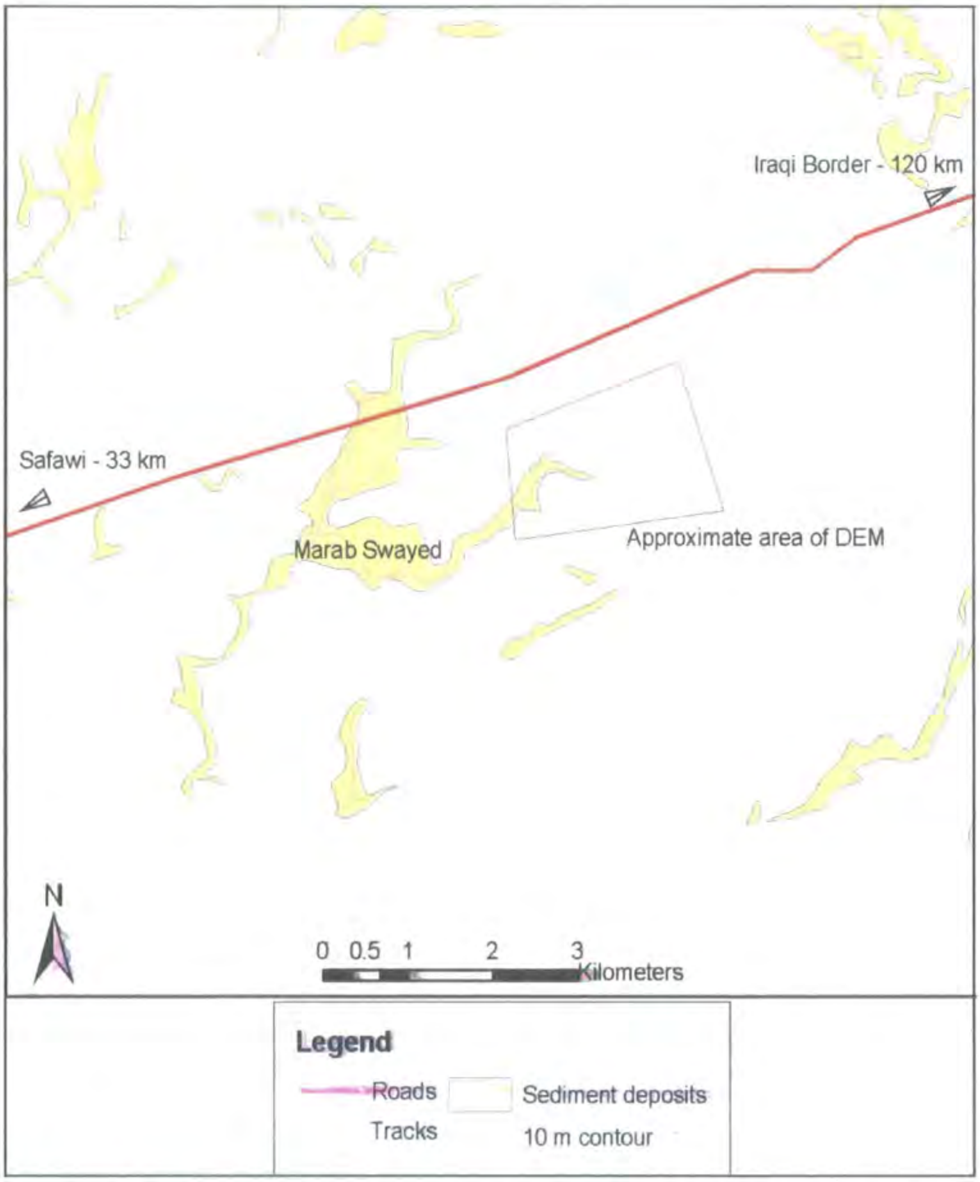


Figure 3.4 Location of DEM survey area relative to Marab Swayed

A highly detailed local DEM was created for this part of the field site. The DEM was derived from an extensive differential global positioning system (DGPS) survey using a Leica Differential GPS System 300. The advantage of the system is the speed of data collection, the ability to survey with only one operative, the high degree of precision in the z-plane and the continuous collection of data points. A temporary bench mark was established on a bedrock outcrop at Marab Swayed as a fixed base-station location. For a period of a week prior to the DEM survey the base-station was placed at the bench mark to gain an accurate location. Ambiguities at the base station location were considered to be less than 0.01 m in x, y and z planes. The bench mark was tied into six local spot heights, previously established by the Royal Jordanian Geographical Centre (RJGC) as a control. WGS84 was preferred over the local co-ordinate system employed by the RJGC (the Jordanian Transverse Mercator (JTM)). WGS84 is compatible with the GIS archive held by the Jordan Badia Research and Development Programme and is commonly supported in GIS. Data was archived daily and post-processed in Safawi. A DEM was created for each day of the survey period such that accuracy could be assessed and any erroneous points could be resurveyed the following day.

After field trials and comparisons with survey results from EDM Total Station surveys, the vertical precision of the GPS was found to be of the order of 0.15 m after geo-correction. The latitude and longitude precision was of the order of 0.05 m. This precision of measurement was obtained for continuous roaming with the rover downloading at 2 s epoch intervals, in addition to greater accuracy for specific *time tagged point* locations such as bench marks. A 3 km by 2 km section of the Marab Swayed drainage system was surveyed over a period of ten days. Transects at 15 m spacing aligned both north to south and a second set east to west were walked across the whole area. A second series of surveys were undertaken in which features were mapped with the GPS, including ridges, breaks of slope, wadi channels, the Marab perimeter and wadi channel deposits. This is used to create a DEM and geomorphological map for whole area. The combination of the two survey approaches provides both a continuous general coveracross the whole survey area and precise detail of key features in the landscape. The resulting data set represented over 45,000 points to a precision of 0.15 m at an average spacing of less than 13 m across an area of 6 km^2. The survey data was imported directly into ArcGIS 8.5, geo-corrected for ionospheric effects and transformed to the WGS84 co-ordinate system. A surface was then interpolated between the survey points using a kriging method, (ESRI, 2002). Distances between test points on the DEM were accurate to 99.9% of the actual distance measured in the field with an EDM in x, y and z planes. A view of the resulting surface is shown in Figure 3.5.

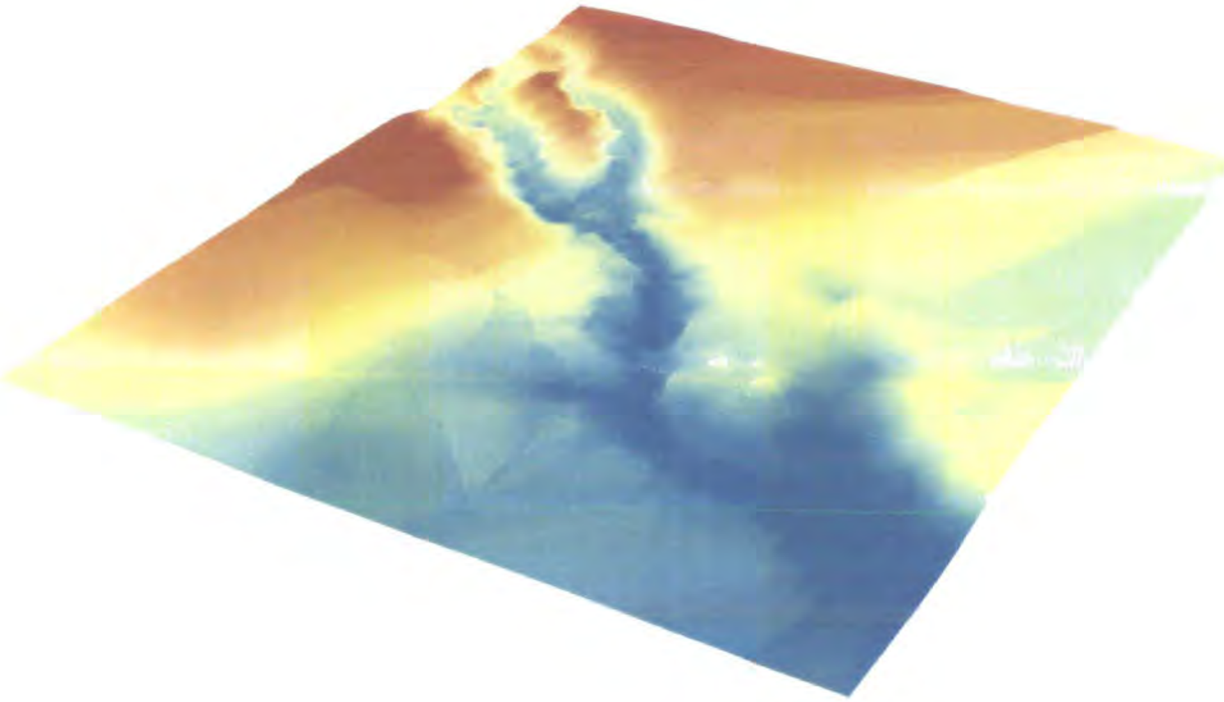


Figure 3.5 Shaded relief image of DGPS derived DEM of Marab Swayed (view oriented southeast, area of view is approximately 8 km²)

The local DEM is used to derive slope form variation in the Marab Swayed region of the northeastern Badia. A slope profile extraction procedure was developed in ArcGIS 8.5 based upon the landscape division proposed by Young (1974). The DEM / GIS allowed the automated identification of the drainage divide and thalweg, using the steepest slope function (ESRI, 2002). A profile base line, a line equidistant from the thalweg and the drainage divide, was overlain (Young, 1974). Slope profiles were then extracted from the surface at roughly 10 m intervals at an angle normal to the profile base line, avoiding atypical topography with the toe location on the thalweg and the crest location at the drainage divide. The profile delimitation is illustrated in Figure 3.6, where the thalweg is represented as a blue line, the profile baseline as a green line, the drainage divide as a red line and the extracted profiles as a black lines, with a blue marker at the toe and a red marker at the crest of each. A total of 228 profiles were extracted from this area (Figure 3.6).

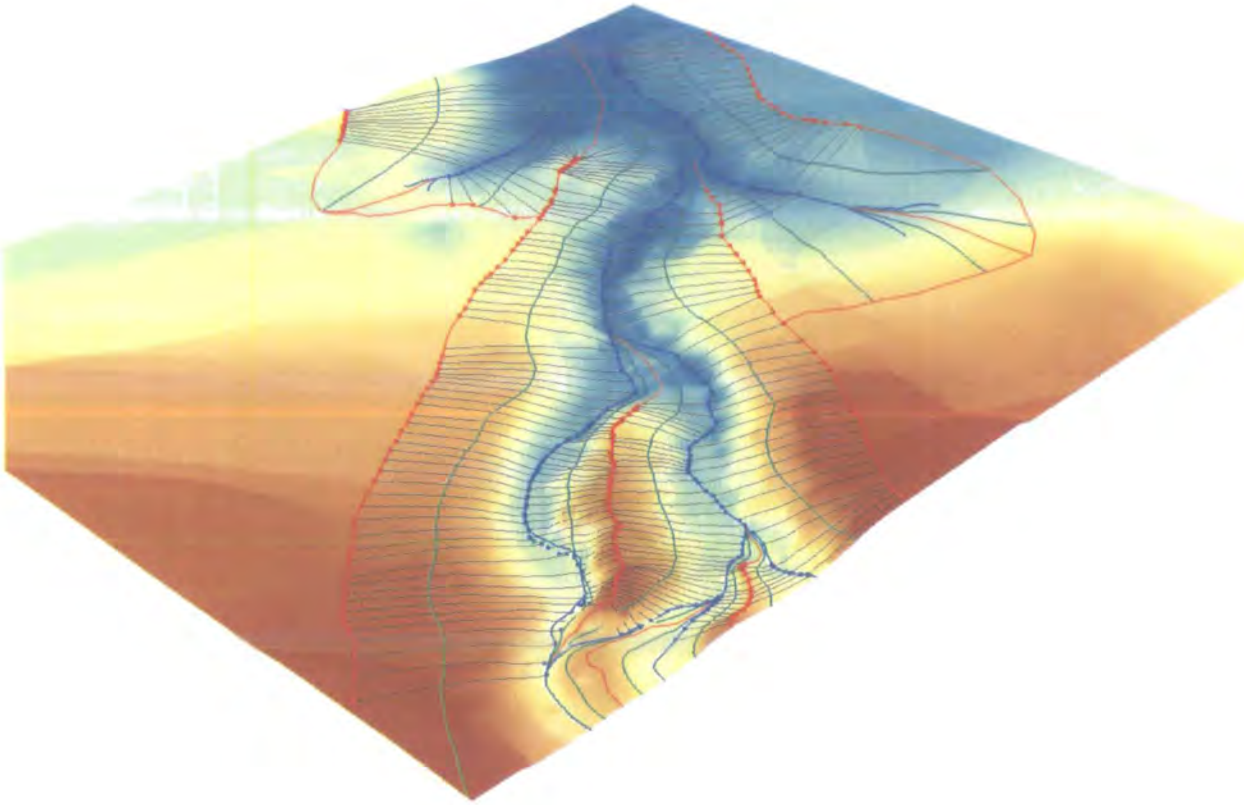


Figure 3.6 Profile extraction at 228 locations, from the DGPS derived DEM (view oriented west, area of view is approximately 8 km^2)

A geomorphological map, developed from the DEM, was then used to examine the location of each profile. Within this study a slope profile of interest was defined as the slope between the drainage divide and the thalweg at an angle normal to the slope profile base line, over clast mantled ground. The study is concerned primarily with linking clast surface form to process. Processes are considered to be significantly different beyond the limits of the boulder cover and these areas are excluded. The active channel or thalweg only occupies a small portion of the wadi bed width. The transport of clasts in the wadi and deposition of finer fluvial sediments clearly defines the boundary of slope relative to channel processes. The boundary was surveyed and overlain in a geomorphological map. The slope profile toe locations were trimmed such that they traverse only the clast mantled portion of the slopes. This was achieved using the geomorphological map as an overlay in the profile extraction GIS (Figure 3.7). The toe position and form of the lower slopes has been shown to have a profound effect on measures of slope form (Young, 1974). This method allowed a consistent and systematic method of profile delimitation.

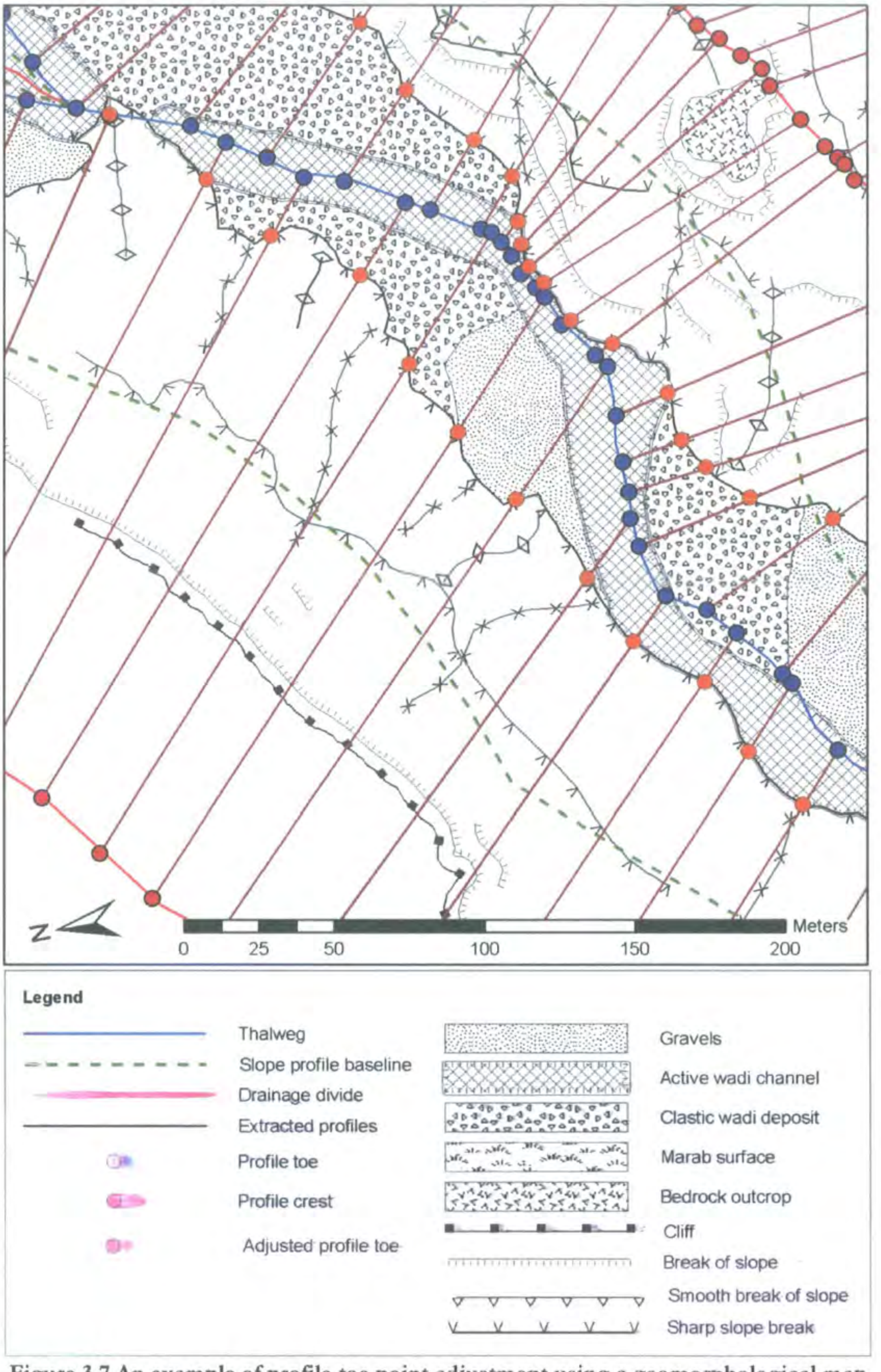


Figure 3.7 An example of profile toe point adjustment using a geomorphological map

The profile extraction generated a two dimensional slope with the origin based at the adjusted toe location, with height and distance from this origin as x and y coordinates. The slope height length integral, termed the Kennedy Parameter (ken.par), was calculated for each of the 228 profiles generated in this manner to assess slope form variation (Allison and Goudie, 1990). Profiles of concave, convex, rectilinear and irregular form were all found to be present within the survey area. Relative relief differences between toe and crest locations is variable, ranging from 0.84 m to a maximum of 25.3 m, with a mean height of 14.36 m. Slope length ranges from 17.6 m to 422.1 m, with a mean length of 150.0 m. Mean whole slope angles range from 0.22° to a maximum of 30.8°, with a mean value of 8.14°, for all 228 profiles surveyed. Slope form is seen to vary between concave and convex, showing two distinct modes focused around ken.par values of 0.461 and 0.630. The bimodal profile distribution represents the either concave or convex slope forms of the sinuous wadi channel. It appears unreasonable to describe typical slope morphology purely in terms of the underlying geology, as previously suggested by Allison & Higgitt (1998). A mean ken.par for all 228 profiles surveyed of 0.534 suggests no 0.115)

and the bimodal distribution of slope forms shows a large variation in profile form (Figure 3.8). The variation in slope form and the geomorphological implications are discussed further in Chapters 4 and 5.

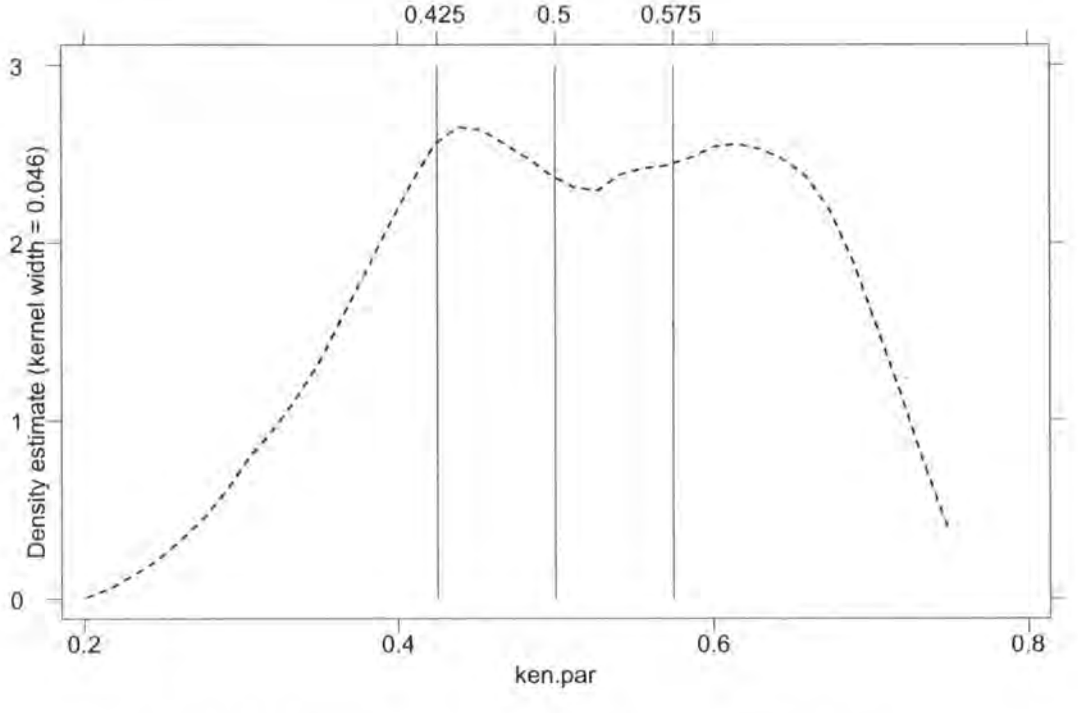


Figure 3.8 Kernel density estimate of ken.par for 228 profiles

For the purposes of sample site selection five potential slope profiles were selected to represent the diversity in ken.par value. Three profiles were selected for the detailed study of slope hydrology and surface form variation.

3.3.4 Slope profile scale

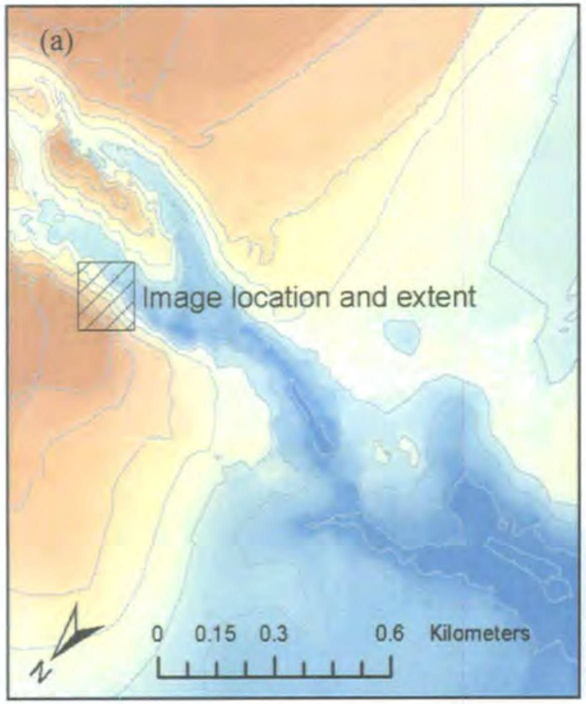
Observation in the field suggests considerable heterogeneity in ground surface clast cover. Anthropogenic disturbance appears important at this scale. Ground disturbance tends to be concentrated around fertile sediment deposits and strategic points. Surface clasts are cleared by Bedu for shelter and camping grounds. Geological anomalies, such as rock outcrops, down slope profiles and archaeological structures, such as desert kites (Helms, 1981), are commonplace. These features are very difficult to identify from the ground. Plate 3.1 illustrates the same area section of the field site as that shown in Figure 3.9, but reveals none of the surface structures that are seen in the aerial image.

Plate 3.1 Oblique photograph of boulder surface

The role of slight variations in topography is difficult to visualise in the field. During winter months overland flow is concentrated into pathways which connect plateau surfaces to the wadi network. Flow pathways form in hollows on the wadi side slopes. The concentration of vegetation growth locates flow pathways shortly after the wet winter season (Plate 3.2).

Plate 3.2 Example of a drainage channel vegetation growth

A method which combines an assessment of topographic variation with a visual representation of the surface was developed to assess the nature of the ground surface and small-scale variation in microtopography. The approach developed employs low-level digital aerial imagery and a highly detailed DEM of the slope. A reconnaissance in the field identified ten potential profile sites. At all of the sites the spacing of survey points in the DEM was increased to an average 2 m separation using DGPS. Vertical digital aerial imagery was obtained for each profile slope. The camera height was maintained at roughly 100 m above the ground, giving the image a ground pixel diameter of 0.12 m and cover of 100 m by 150 m. To account for slope the images were geo-corrected to 10 uniformly spaced ground control points, which were surveyed with the DGPS. The resulting image was overlaid on the DEM in ArcGIS 8.1, to assess the variation in ground surface cover and identify any anomalies in the clast cover (Figure 3.9). The aerial images demonstrate the presence of geological features which are difficult to identify on the ground. Variations in ground cover related to swales and hollows across the slope profile. Using the qualitative method of assessment, three profiles were selected from a sample of ten. They were chosen firstly for their diversity of profile forms and secondly for the continuity and consistency in ground surface coverage.



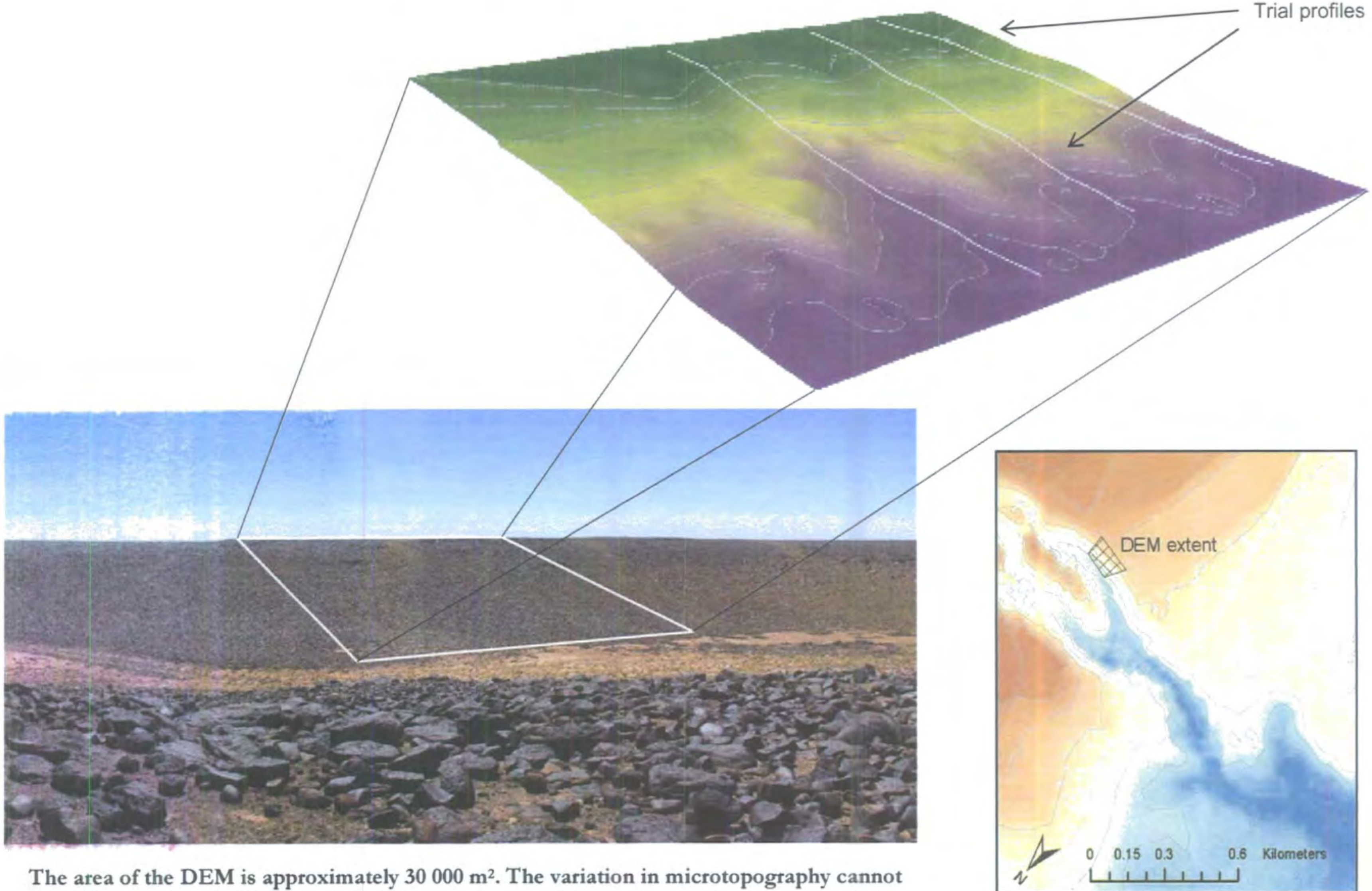
(a) location of example of aerial image; (b) Aerial digital image, captured from a camera height of 100 m, showing a whole concave slope profile (Profile CC). The arrow indicates the direction of slope.

Key:

(1) Location of camera for image in Figure 3.5 and approximate field of view represented by white lines; **(2)** Geological anomaly; **(3)** Wadi bed at slope toe; **(4)** Bedrock outcrop at slope crest.

Figure 3.9 Identification of atypical ground cover from aerial imagery

Figure 3.10 Detailed DGPS derived DEM, with 1.5 times vertical exaggeration, wit 2 m contours



The area of the DEM is approximately 30 000 m². The variation in microtopography cannot easily be seen in the field. The only indication is given by grasses growing preferentially in topographic lows on side slopes during spring. Colour is applied to emphasise microtopographic variability.

3.3.5 Plot scale

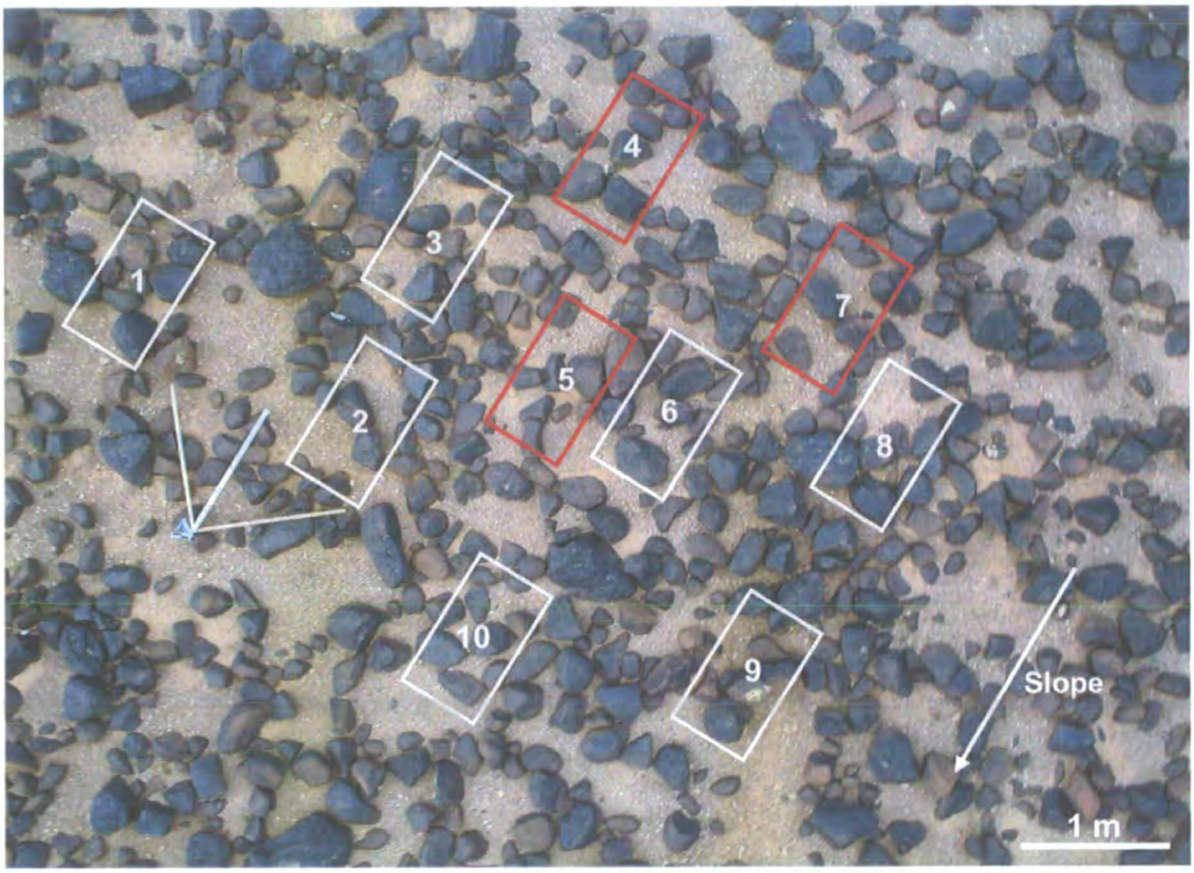
Plot location at the slope scale loosely follows the methodology developed by Allison and Higgitt (1998). This method systematically locates plots at five points down the slope profile at set intervals. Plots are located at the crest (Top), the midpoint (Middle) and toe (Bottom), with two additional plots evenly spaced in between, named upper (Upper) and lower (Lower). Considerable success in identifying the absolute changes in ground surface form from slope crest to toe has been previously achieved with this sampling framework (Allison *et al.*, 2000). The use of five sample points retains enough resolution to examine surface form variability, without measuring all clasts on a profile. The selected profiles are located on the DEM, total profile surface length is calculated and plot locations systematically located at even intervals down the profile length. The aerial images are then used to verify the suitability of each plot position relative to atypical ground surface coverage. The co-ordinates of plot location are downloaded to the DGPS as waypoints, which can then be navigated to and relocated in the field.

The field based research in this thesis is two-fold: first surface characterization, and second, an assessment of surface hydrology. The two strands of the research require different methods of plot location. The surface characterization technique (Chapter 4) is based on a plot area of roughly 8 m by 6 m, a total of 32 m^2. This plot is qualitatively located again using the high altitude image obtained from 100 m for each slope (Figure 3.11), and the high resolution DEM. This mechanism avoids atypical ground surface cover and other anomalies on the surface. The experiments on surface hydrology (Chapter 5) are logistically restricted by plot size to an area of 0.5 m^2, 0.5 m by 1.0 m. To assess the degree of heterogeneity in surface hydrology three experiments at three separate plots were conducted at each sample point. A plot of this size is subject to heterogeneity in surface hydrology, irrespective of the presence and variation of surface clast cover (Agnew and Anderson, 1992). The heterogeneity of ground surface coverage, especially where a non-uniform surface distribution is present, can only act to exacerbate this effect.

(A) – clast removal in preferential flow path; (B) atypical ground disturbance

Figure 3.11 Example (midpoint of profile ST) of the location of the surface characterization plot within the 100 m altitude aerial image

A quantitative method of locating the plots used to examine the surface hydrology was developed. The objective was to delimit a plot of 0.5 m^2, within which the ground surface cover represents the mean ground surface cover of the whole image analysis plot (32 m^2). At the crest, toe and mid-point of the three slope profiles selected, 10 randomly located plots of dimensions 0.5 m by 1.0 m were positioned within the area of the image analysis plot. A basic measure of surface form for each plot was derived, using the method developed in Chapter 4. Surface hydrology plots are always oriented with their long axis downslope. The three plots with the closest mean percentage ground coverage, mean edge length and mean intermediate axis dimensions to that of the whole surface of the characterization area were selected for the surface hydrology experiments (Figure 3.12). Each hydrology plot can then be considered to be statistically representative of the mean character of the surface at that sample point on the slope profile. The co-ordinates of the four corners of the selected plots were located within ArcGIS 8.1, and then navigated to in the field using the DGPS.



Plot	Whole image	1	2	3	4	5	6	7	8	9	10
Percentage cover (%)	**35.88**	67.89	22.14	41.65	**36.40**	**33.67**	50.54	**37.62**	57.93	55.00	39.64
Mean edge length (m)	**0.479**	0.556	0.602	0.337	**0.462**	**0.501**	0.764	**0.446**	0.655	0.563	0.462
Mean intermediate axis (m)	**0.125**	0.298	0.462	0.527	**0.201**	**0.169**	0.155	**0.487**	0.552	0.110	0.722

Figure 3.12 Example of the location of hydrology plots within the surface characterization plot and mean surface characteristics for each plot (example - CV middle)

3.3.6 Subplot scale

Although it is not necessary to further define a link to a lower scale than the plot, the sub-plot remains of critical importance. The sub-plot scale is that at which the level of variation between individual clasts is apparent and is the scale at which many of the processes on the surface act. It is at the sub-plot scale that the surface characterization and surface hydrology addresses variability in surface form and process through high precision and accuracy of measurement. The nature of the study is such that small scale variations in form and process can be aggregated up to the plot scale, to evaluate geomorphological variations between disparate locations. It is hoped that the precision of the techniques employed is such that data at the sub-plot scale that is of relevance, and is appropriate to the investigation, can be collected from the plot scale.

The development of a semi-quantitative, nested sampling strategy based on a consideration of scale, location and adequacy has selected a series of 7 sites, with a total of 35 sample points. Within the sampling framework, variations both within and between basalt types can be assessed. Three sites have been selected to specifically explore the link between slope form and process in the context of a single basalt. Additionally, sample sites have been selected such that comparisons between surface form can be compared between geologies. Logistical limitations and the requirement for highly accurate and detailed data mean that not all experiments, specifically the surface hydrology, can be conducted within the scope of this study. The approach favours a concentration of intensive studies at a series of statistically selected sites, rather than aggregated statistics more crudely collected from qualitatively located plot locations.

3.4 Site descriptions

The role of each site selected for the study has a different purpose. The level of investigation at each site varies due to the purpose of the investigation at each slope profile, which is ultimately dictated by logistical constraints (Table 3.3). Sites CC, CV and ST are the focus of the investigation. CC, CV and ST are abbreviations of concave, convex and straight, respectively, referring to the slope form of each profile. At each of the three profiles surface character and surface hydrology are assessed. The location of the sites allows comparison both within and between basalt types, on a variety of slope forms. At the remainder of sites surface character is assessed alone. A greater level of description is given at sites CC, CV and ST, which is of relevance to the extrapolation of results from the surface hydrology characterisation. The description of each site includes location, topography, slope form, geology, geomorphological setting, ground photographs, and in addition at CC, CV, and ST, sediment character and large scale aerial images of the whole slopes are presented.

Site	Sample point	Name	Surface characterisation	Surface hydrology
Concave		CC		
	Top	CCT	×	×
	Middle	CCM	×	×
	Bottom	CCB	×	×
Convex		CV		
	Top	CVT	×	×
	Middle	CVM	×	×
	Bottom	CVB	×	×
Straight		ST		
	Top	STT	×	×
	Middle	STM	×	×
	Bottom	STB	×	×
Swayed 1		SW1		
	Top	SW1T	×	
	Upper	SW1U	×	
	Middle	SW1M	×	
	Lower	SW1L	×	
	Bottom	SW1B	×	
Swayed 2		SW2	×	
	Top	SW2T	×	
	Upper	SW2U	×	
	Middle	SW2M	×	
	Lower	SW2L	×	
	Bottom	SW2B	×	
Qa'a al Buqei'wiya 1		GW1		
	Top	GW1T	×	
	Upper	GW1U	×	
	Middle	GW1M	×	
	Lower	GW1L	×	
	Bottom	GW1B	×	
Qa'a al Buqei'wiya 2		GW2		
	Top	GW2T	×	
	Upper	GW2U	×	
	Middle	GW2M	×	
	Lower	GW2L	×	
	Bottom	GW2B	×	
Total			29	9

Table 3.3 Field site names and description of investigation

3.4.1 CC - site description

CC was selected to assess the link between surface form and surface character on a concave profile form (Figure 3.13). The profile crest is located on a bedrock outcrop, where jointing structures and rockfalls are evident. At the crest location the ground surface is dominated by bedrock and large angular clasts. The surface of the slope is typical of Aded basalt, exhibiting an open matrix of sharp, well varnished clasts, with a large mean size. The nature of surface character changes downslope and in places is distinctly non-randomly distributed. The profile toe is at the margin of the wadi bed and is clearly defined by a rapid change in ground cover and slope angle (Figure 3.14). No evidence of ground disturbance is apparent. Vegetation is all but non-existent throughout the year. Figure 3.15 is a high altitude aerial image (100 m) of the profile location, showing nearby geological anomalies and the structures in the wadi bed at the slope toe. A noticeable transition in the ground surface sediment character is apparent (Figure 3.16), with fine basalt fragments at the crest, whereas fine light coloured silts and clays dominate the toe locations. Plate 3.3 is an oblique photograph of the profile. Plate 3.4 is a low level image (12 m) of the profile midpoint.

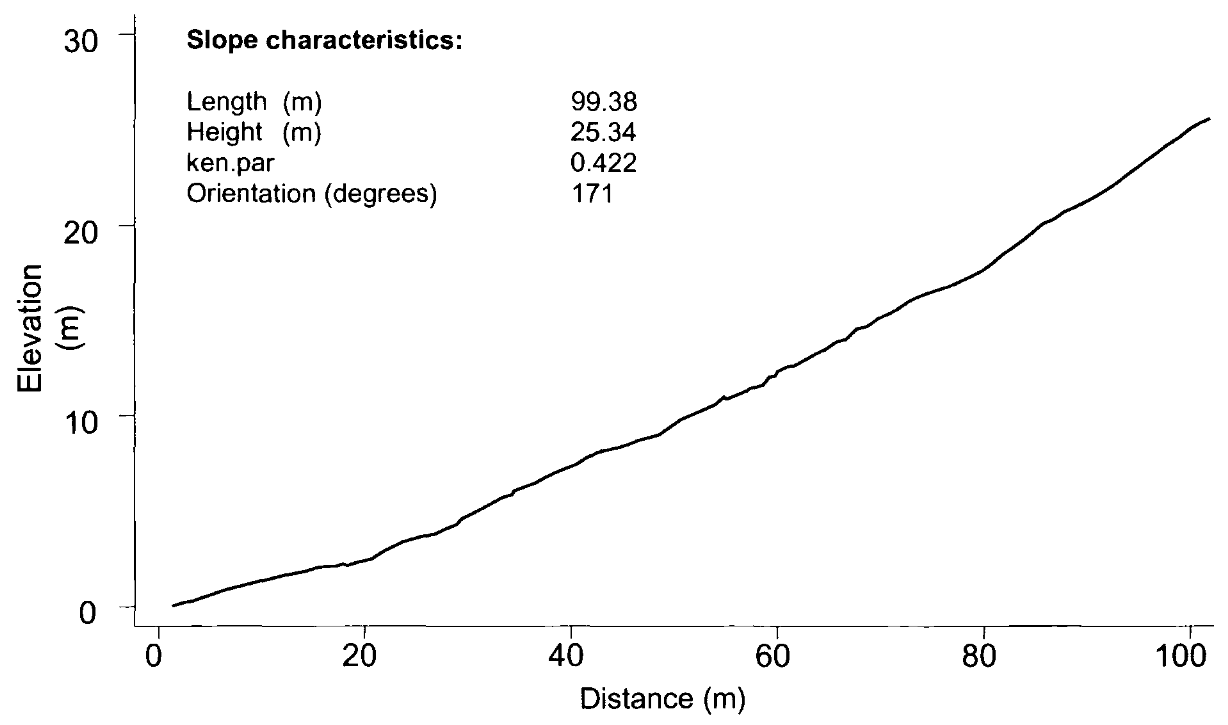


Figure 3.13 CC – Slope profile form description

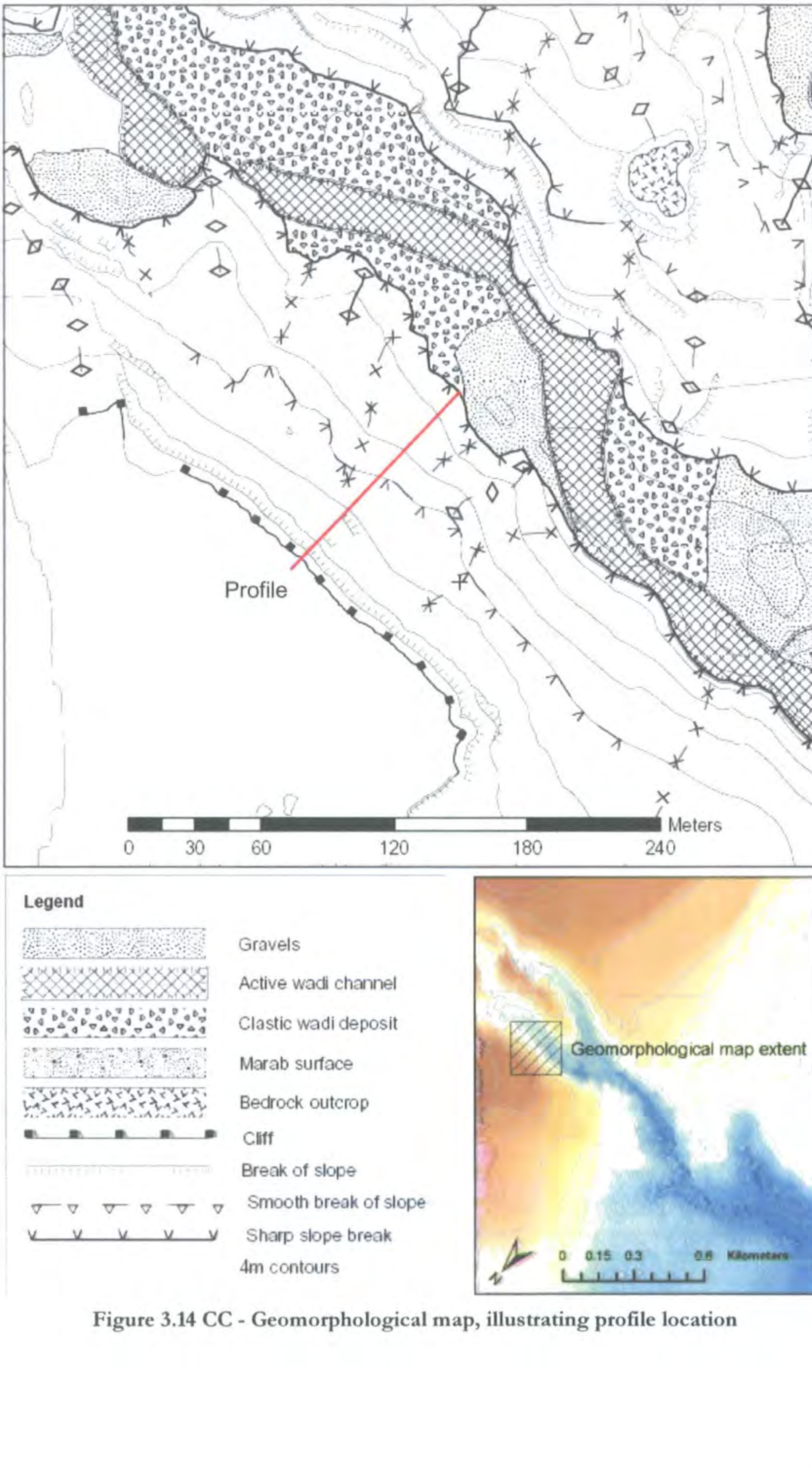


Figure 3.14 CC - Geomorphological map, illustrating profile location

Figure 3.15 CC - 100 m altitude aerial image, showing profile location

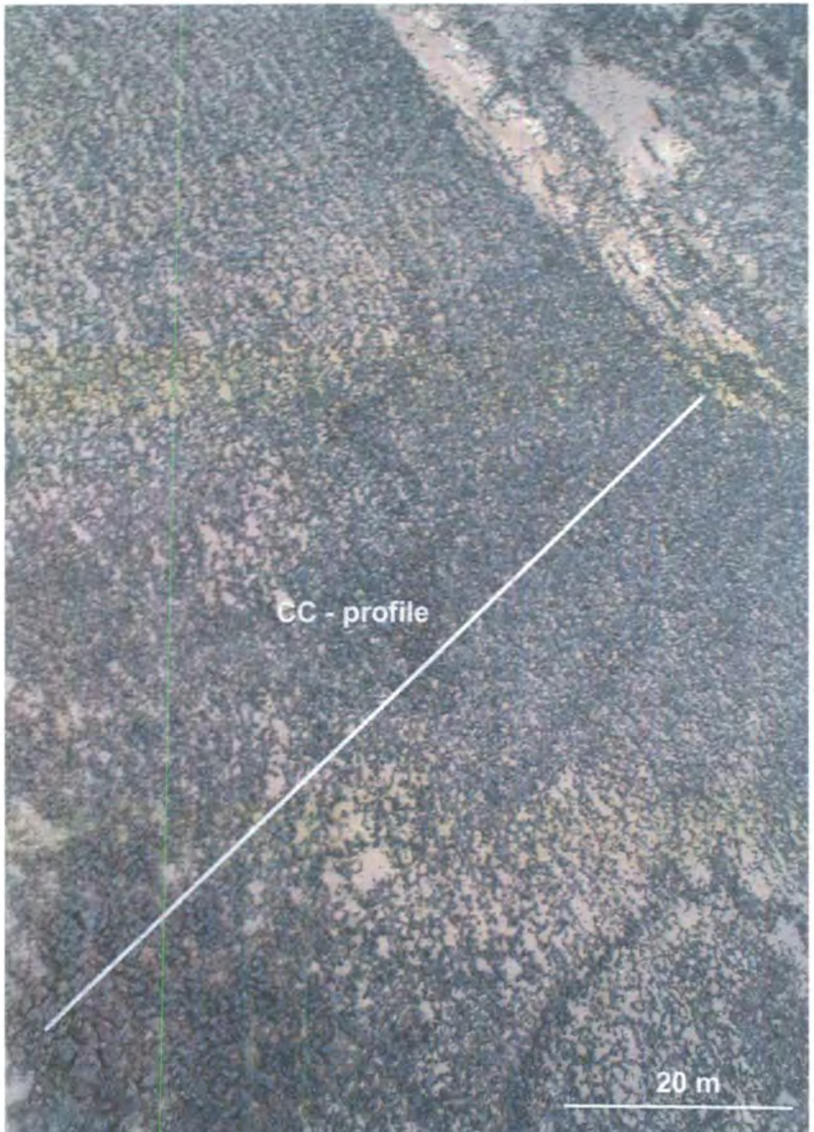
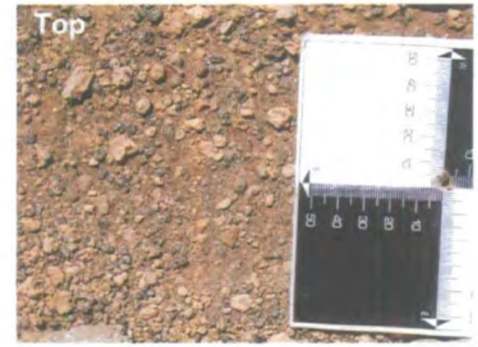


Figure 3.16 CC – sediment surface photographs (scale in mm)



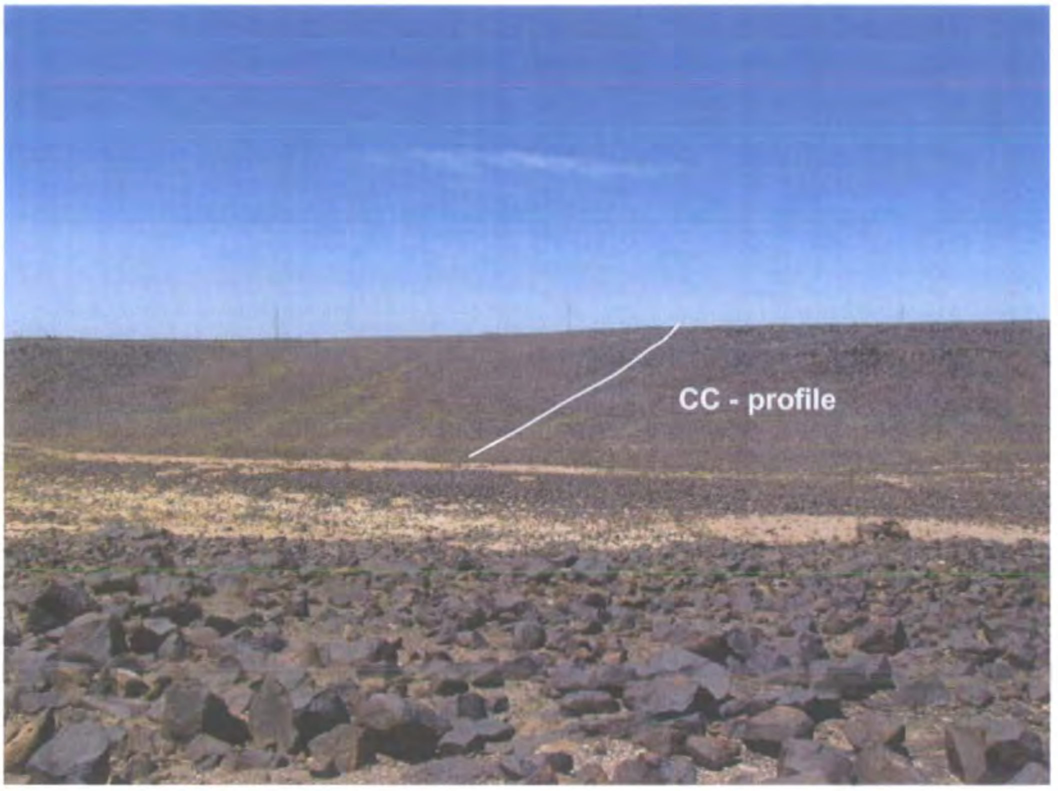


Plate 3.3 CC - Oblique photograph of profile

Plate 3.4 CC - Example of ground surface cover (example CCM)

3.4.2 CV – site description

CV is a convex profile site specifically selected to look at the linkage between form and process on a convex slope (Figure 3.17). Its location is close to ST and CV, such that the geology can be considered the same. The slope is located on a basalt outcrop which is incised on two sides by deep wadi channels (Figure 3.18, Plate 3.5). The profile toe is bounded by an abrupt transition to wadi bed gravels and a distinct break of slope. The ground surface is typical of the Abed basalt exhibiting an open matrix with large clasts (Plate 3.6). A distinct variation in both clast and sediment surface character is noted between the crest, midpoint and toe plot locations (Figure 3.19). There is only limited evidence of carbonate deposits both at and beneath the surface (Figure 3.20). There is considerable evidence of gypsum deposits at the margin of the weathered bedrock in the soil profile.

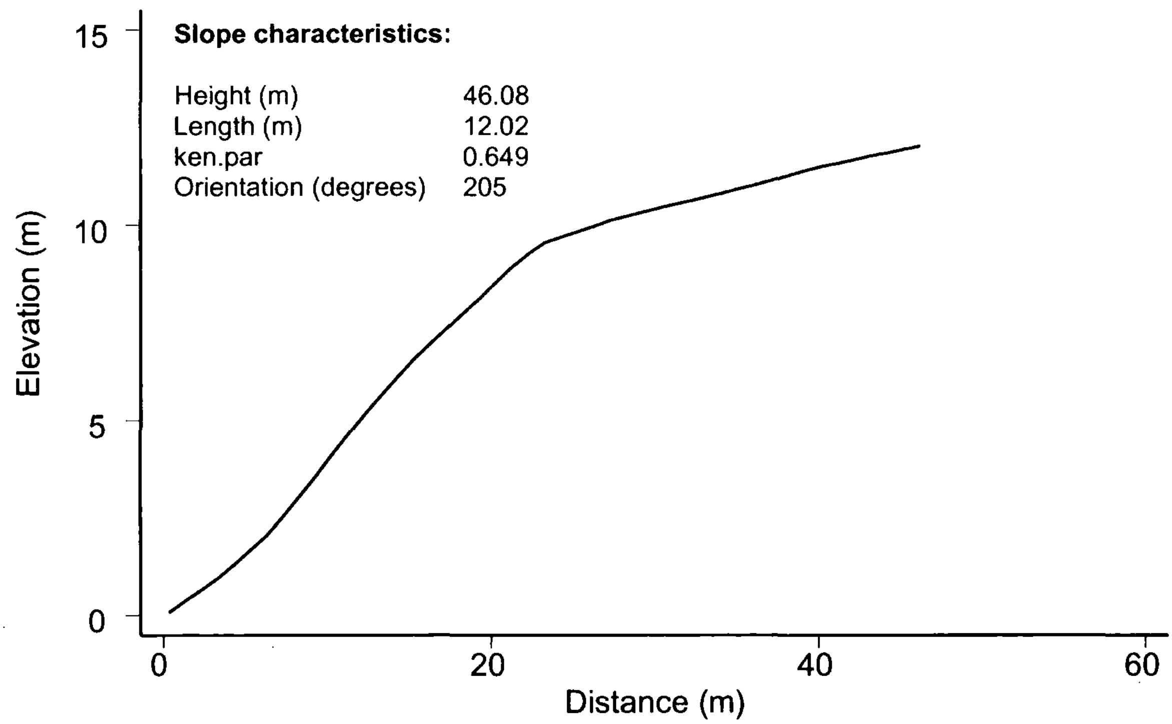


Figure 3.17 CV – Slope characteristics

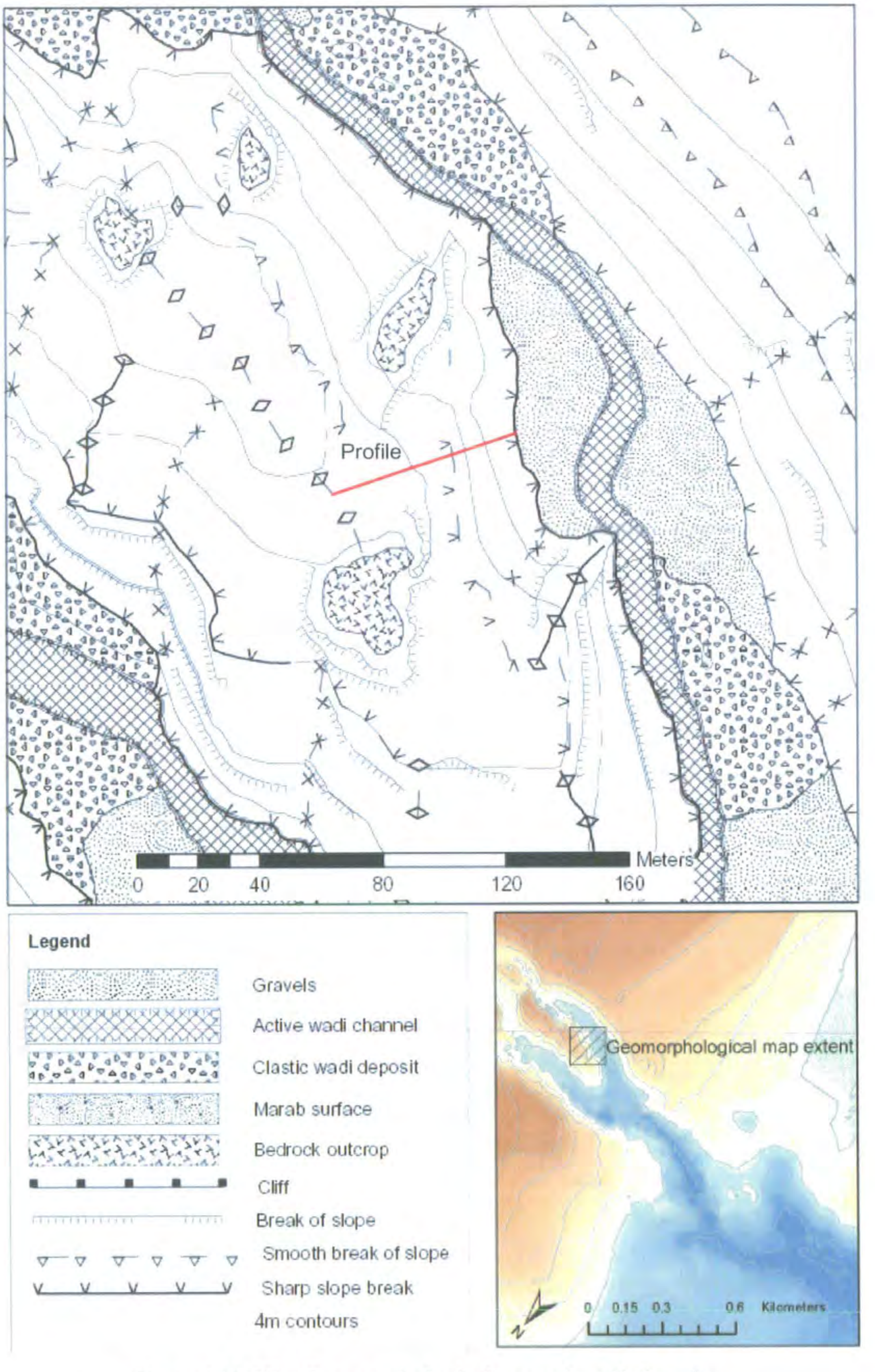


Figure 3.18 CV – Geomorphological map of profile location

Figure 3.19 CV – 100 m altitude aerial images. The arrow indicates slope direction and the scale bar = 10 m

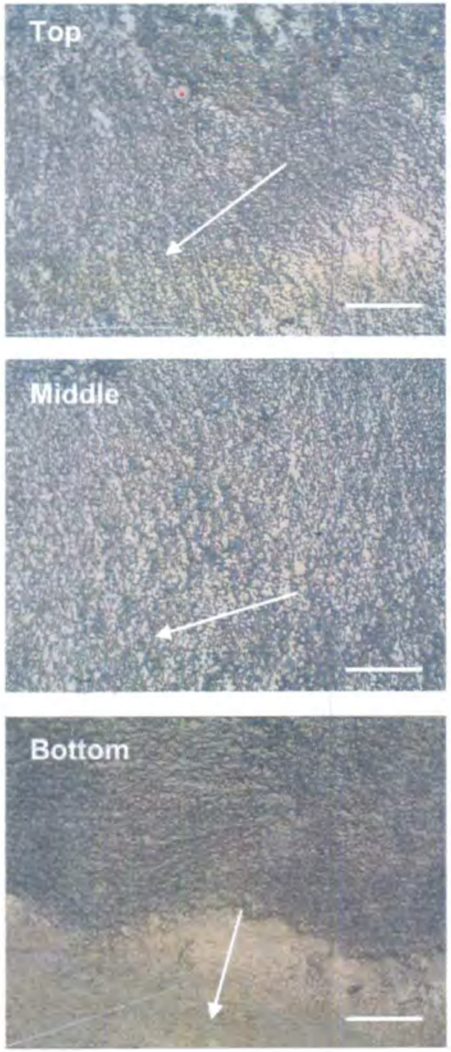
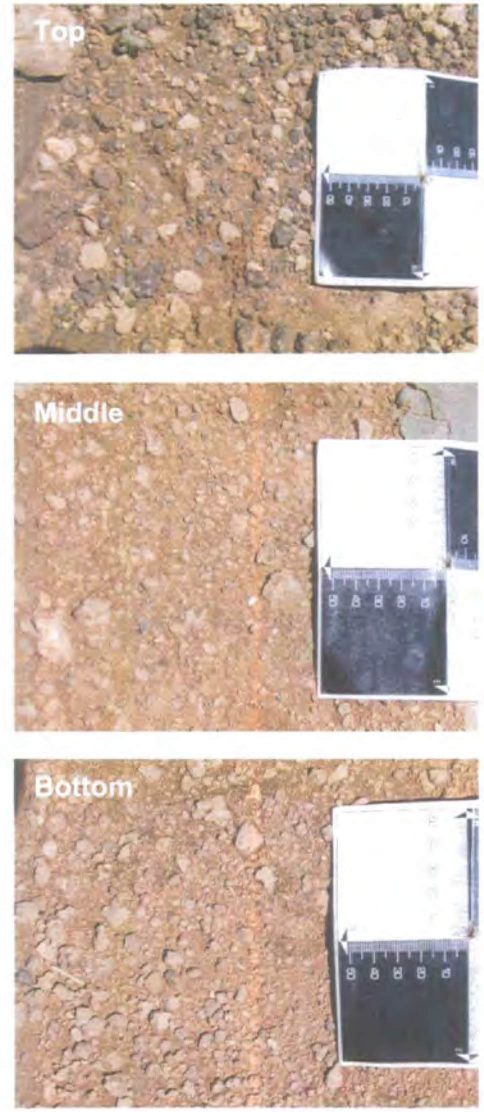


Figure 3.20 CV – sediment surface images (scale in mm)



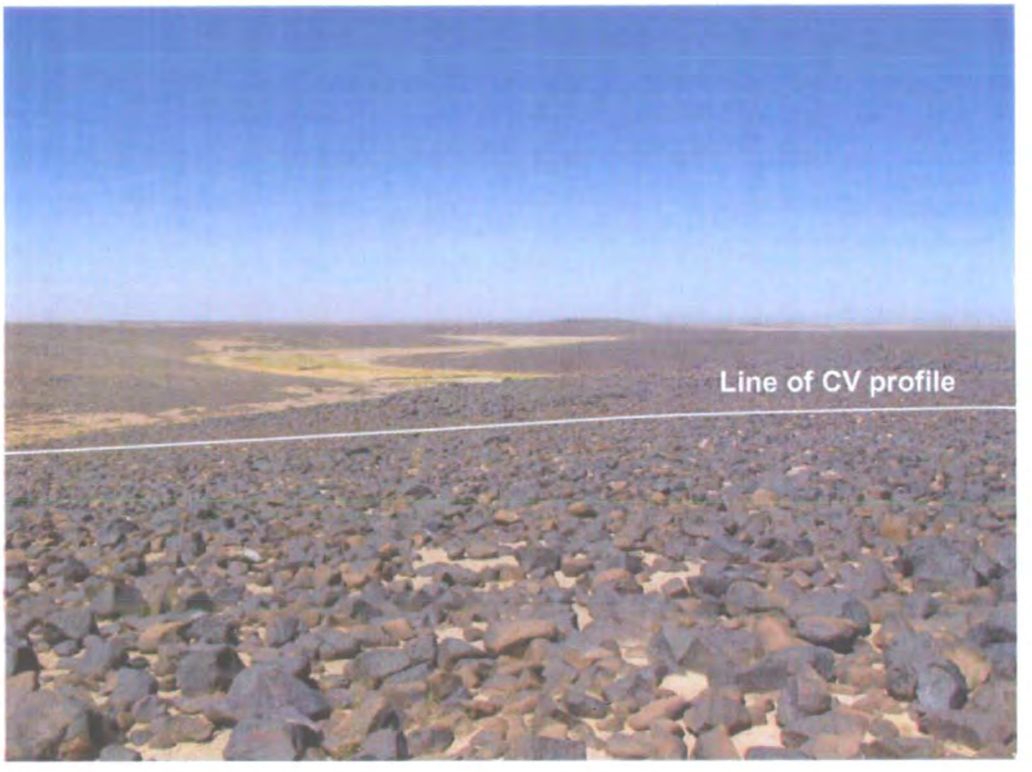


Plate 3.5 CV - Oblique photograph looking over profile

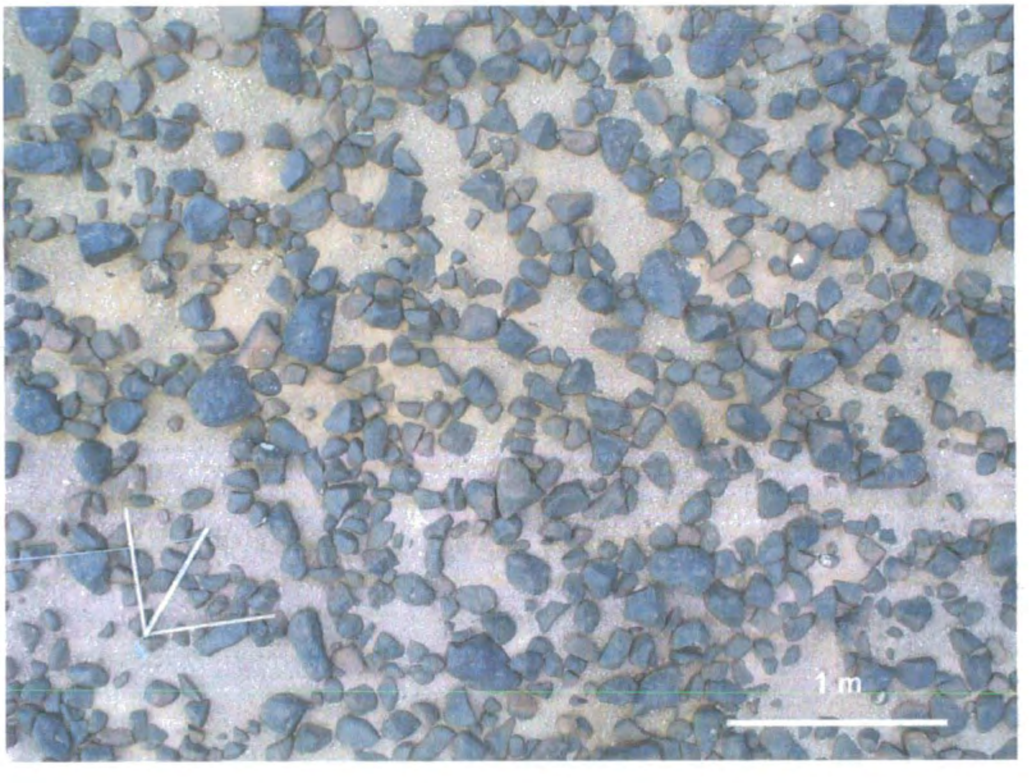


Plate 3.6 CV - Example of ground surface cover (CVM)

3.4.3 ST – site description

ST was selected as a test of the relationship between slope form and process on an effectively rectilinear or straight profile (Figure 3.21). As such this location acts as a control for the other sites in this study, where the complication of convexity or concavity is absent. The crest of ST is at a bedrock outcrop, but at a significantly lower angle than that at CV (Figure 3.22). The profile shows variation in surface character between the crest and the toe location, with considerable evidence of non-random clasts distributions (Figure 3.23, Plate 3.8). The clast cover is typical of Abed basalt surfaces (Plate 3.8, Plate 3.7). Considerable ground disturbance is apparent at the toe location. The bottom plot location was carefully positioned to avoid such disturbance. The ground surface at the slope crest is dominated by carbonate nodules and fine basalt fragments, whereas the toe of the slope has significant aeolian deposits (Figure 3.24).

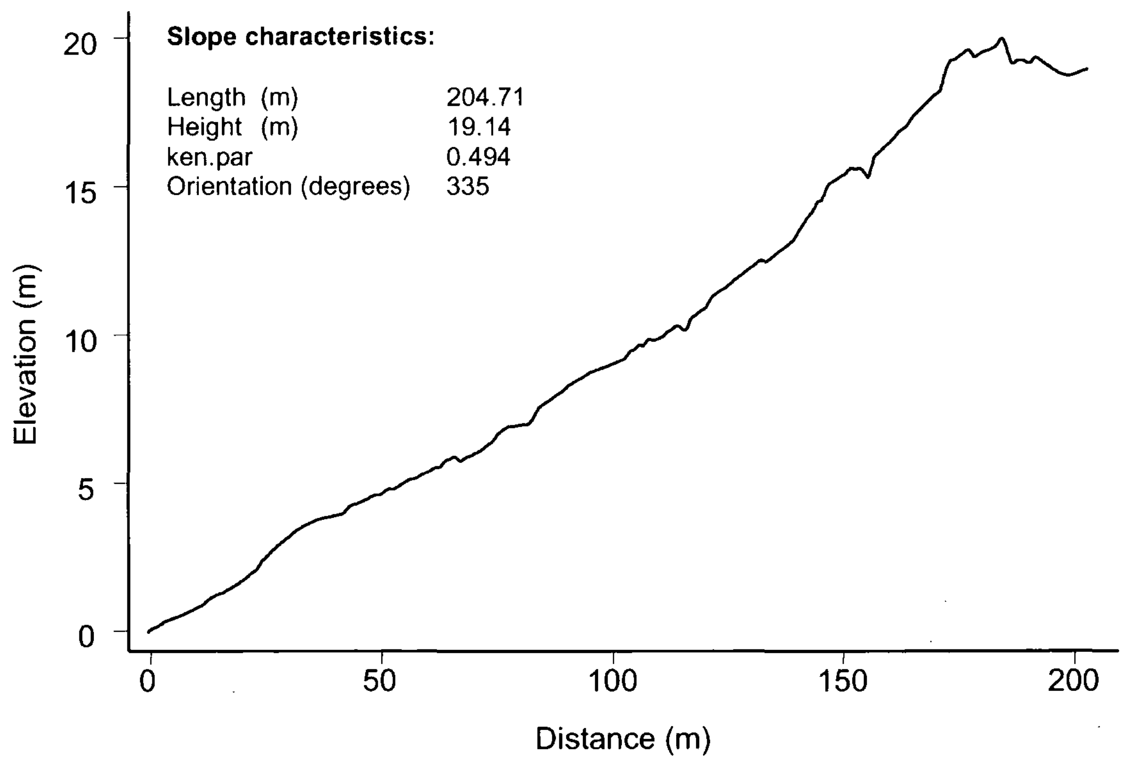


Figure 3.21 ST – Profile characteristics

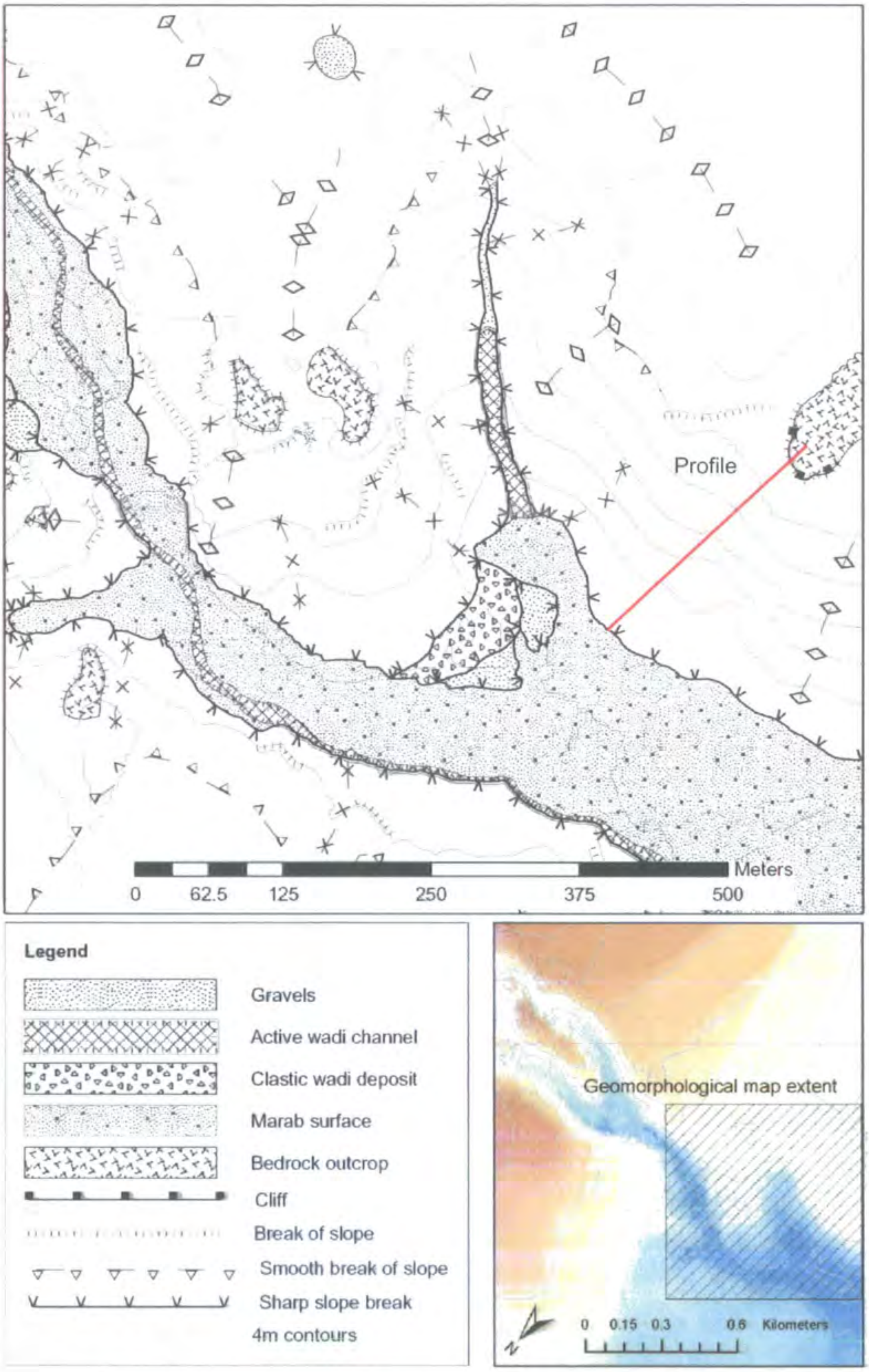


Figure 3.22 ST – Geomorphological map showing profile location

Figure 3.23 ST – 100 m altitude aerial images. Arrow points downslope and scale bar = 10 m

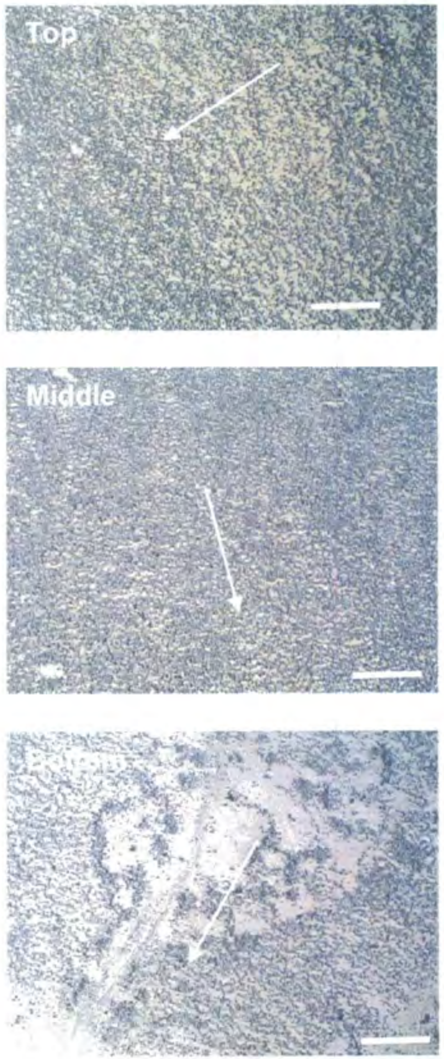


Figure 3.24 ST – Sediment surface photographs (scale in mm)

Plate 3.7 ST - Oblique photograph looking down profile from crest (pickup in distance for scale)

Plate 3.8 ST – Example of ground surface coverage (STM)

3.4.4 SW1 and SW2 – Marab Swayed

Sites SW1 and SW2 were located at Marab Swayed (Figure 3.25), avoiding ground disturbance and atypical microtopography. The two sites act as comparisons for the results of the surface characterization generated from CV, CC and ST and allow within-basalt comparisons to be made on a larger sample of slope profiles. The two profiles are located further down the Marab Swayed catchment, where the channel of the Marab is less constricted and the side slopes are significantly shallower.

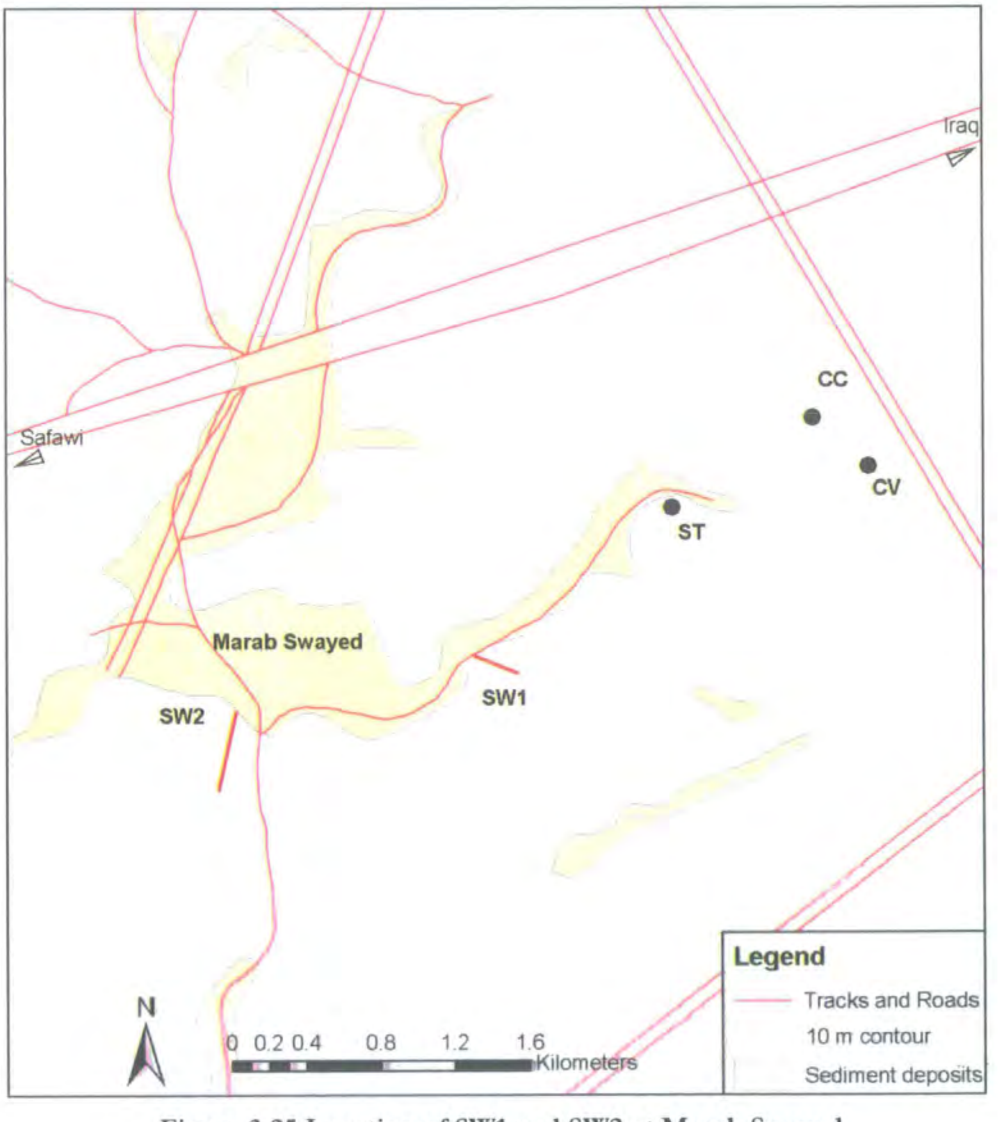


Figure 3.25 Location of SW1 and SW2 at Marab Swayed

3.4.5 SW1 – site description

The crest of profile SW1 is located on a bedrock outcrop. The profile is on one of the series of truncated spurs on the Marab side slopes as it becomes progressively constricted up catchment (Figure 3.25). The profile toe is located on the flanks of the Marab surface, in an exposed position (Plate 3.9). The profile is effectively rectilinear (Figure 3.26), and exhibits some of the best evidence of non-random distribution of surface clasts (Plate 3.10). Variations in ground surface cover are visible in the field between disparate plot positions downslope. The surface is typical of Abed basalt, with some a greater level of lichen growth (Plate 3.10). Additionally, aeolian deposits are more significant at the toe, as are carbonate nodules.

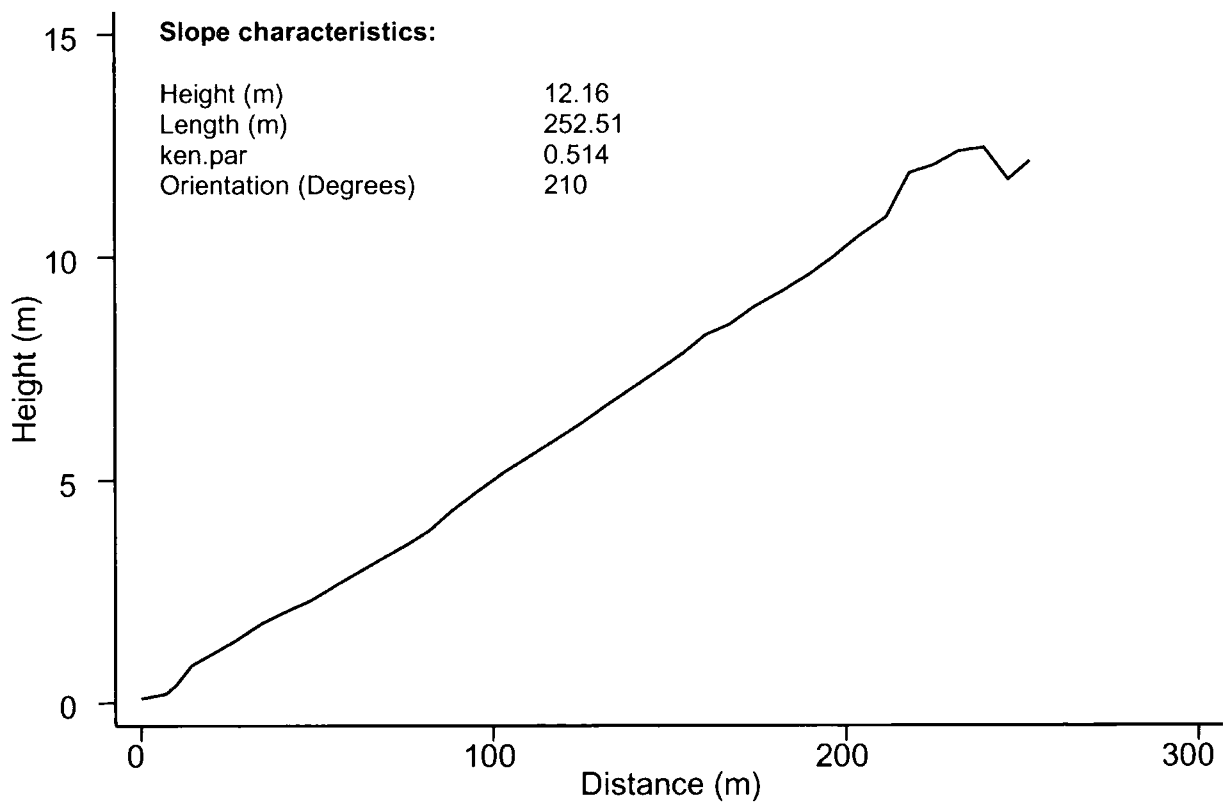


Figure 3.26 SW1 – Profile characteristics

Plate 3.9 SW1 - Oblique photograph looking across profile, looking west down the Marab Swayed catchment towards Safawi

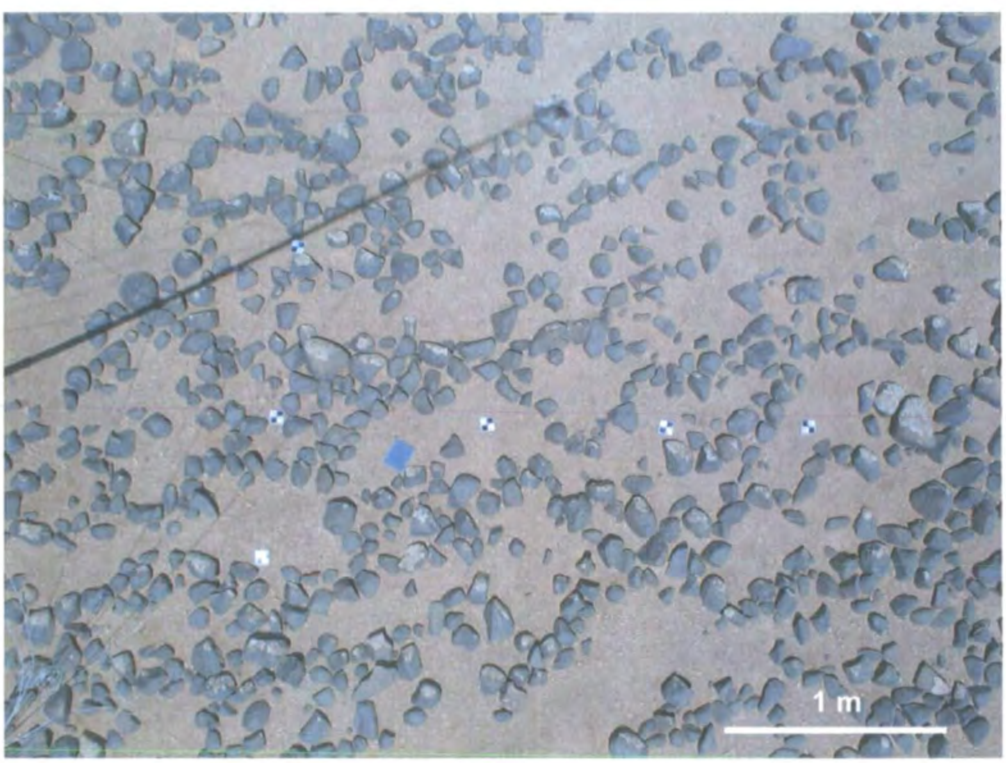


Plate 3.10 SW1 - Example of ground cover with noticeable non-random clast distributions (SW1M)

3.4.6 SW2 – site description

Profile SW2 is the longest and shallowest angled slope used in this study. The profile crest is positioned on a bedrock platform at the drainage divide of Marab Swayed and the toe is located at the Marab edge (Plate 3.11). The profile form is rectilinear (Figure 3.27). The definition of the Marab edge is not clear as clasts become progressively deeper buried to the slope toe. Evidence of inundation by standing water at the toe locations is apparent. Scour marks around clasts indicate high velocity overland flow. The site shows some variation in surface character, but this is not as marked as that seen at SW1, or further up the catchment. The clasts at the site appear to be smaller and have a more rounded texture than those at the other sites (Plate 3.12). The underlying sediments throughout the slope profile are fine silts and clays with few carbonate or aeolian deposits apparent.

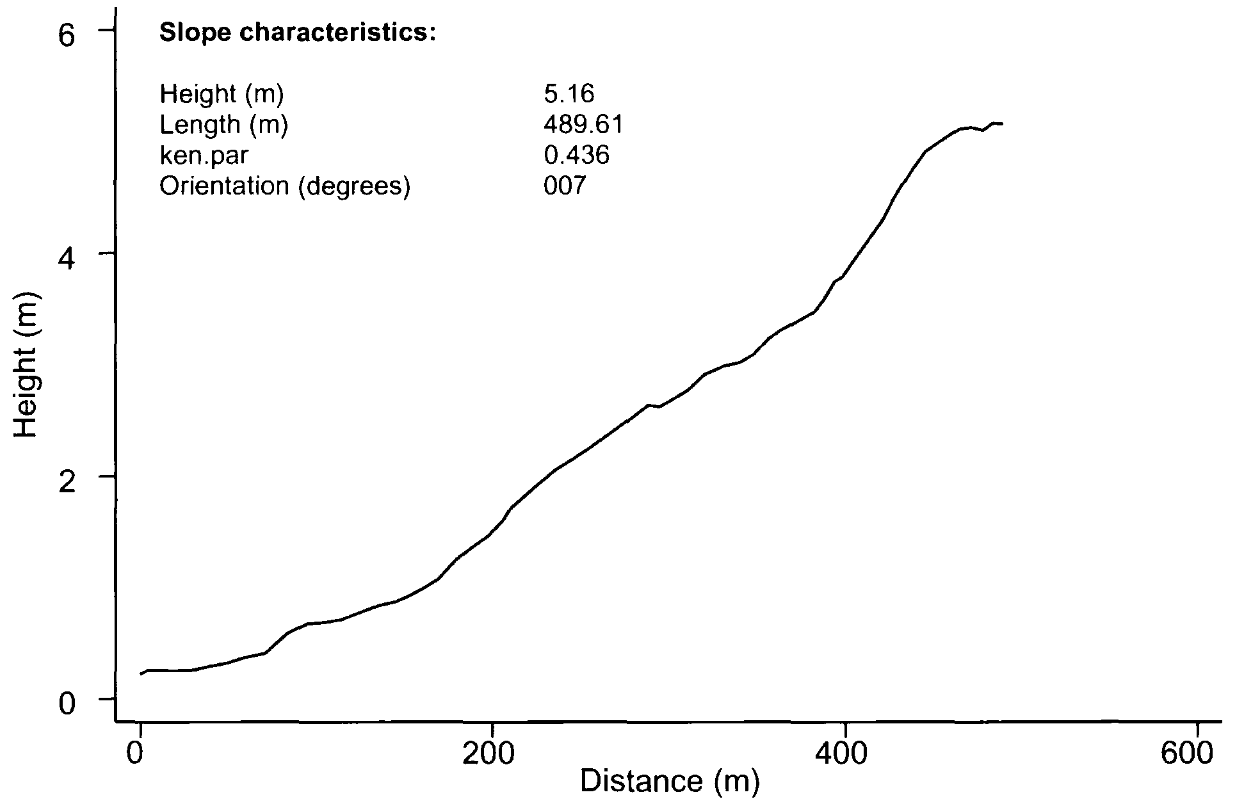


Figure 3.27 SW2 - Slope profile characteristics

Plate 3.11 SW2 - Profile location taken from profile base looking upslope to the crest on the horizon. The Marab floor in the foreground is dominated by coarse sediments.

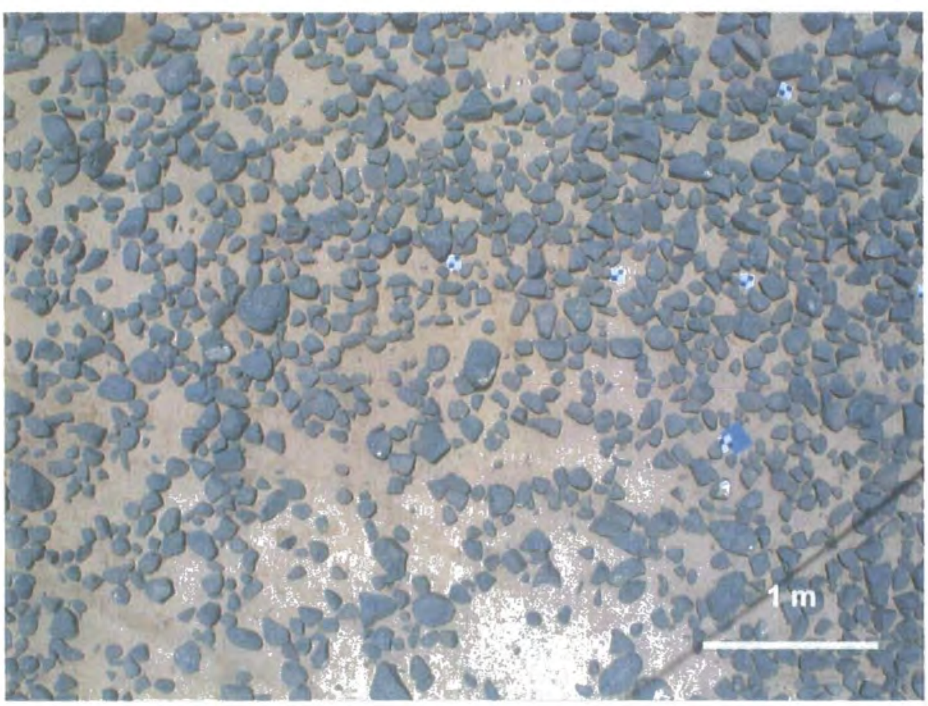
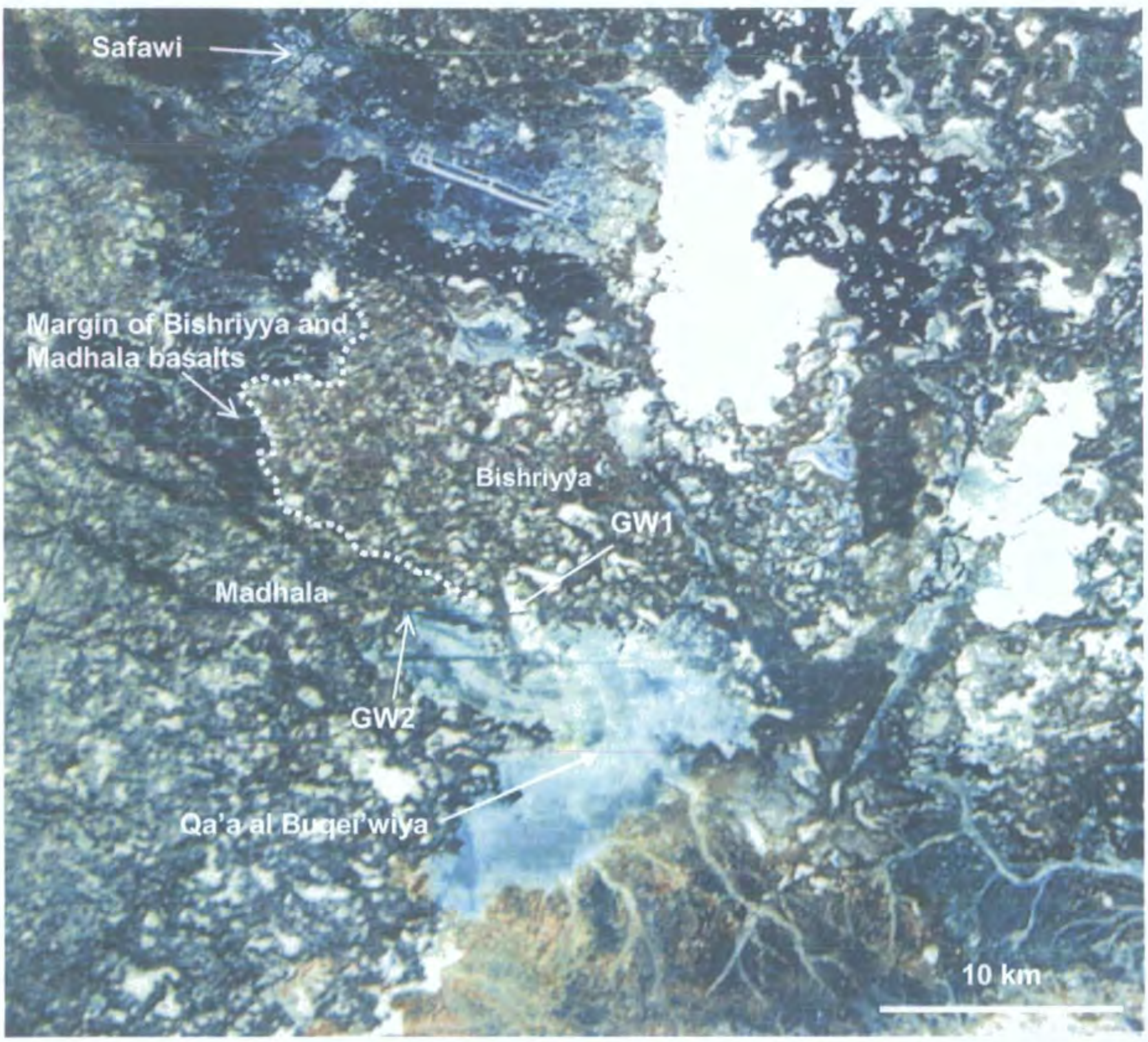


Plate 3.12 SW2 – Typical ground surface coverage, showing a high degree of clast rounding (SW2M)

3.4.7 GW1 and GW1 - Qa'a al Buqei'wiya

The sites at Qa'a al Buqei'wiya were selected to enable comparison between two further basalt types. The location of Qa'a al Buqei'wiya relative to Marab Swayed and Safawi is shown in Figure 3.29. The site locations (Figure 3.29) were selected in the field, avoiding atypical microtopography and atypical ground surface cover. Both profiles are located on the northern margin of the Qa'a. The two profiles are based on separate basalts, GW1 on the Bishriyya, and GW2 on the Madhala, the limits of which can be identified on the LandSat TM image (Figure 3.28).



(Bands 7, 4, 2; path 173, Row 32.12N, Date 29.03.92; Huntings Technical Services)

Figure 3.28 LandSat TM image of Qa'a al Buqei'wiya, highlighting the location of GW1 and GW2

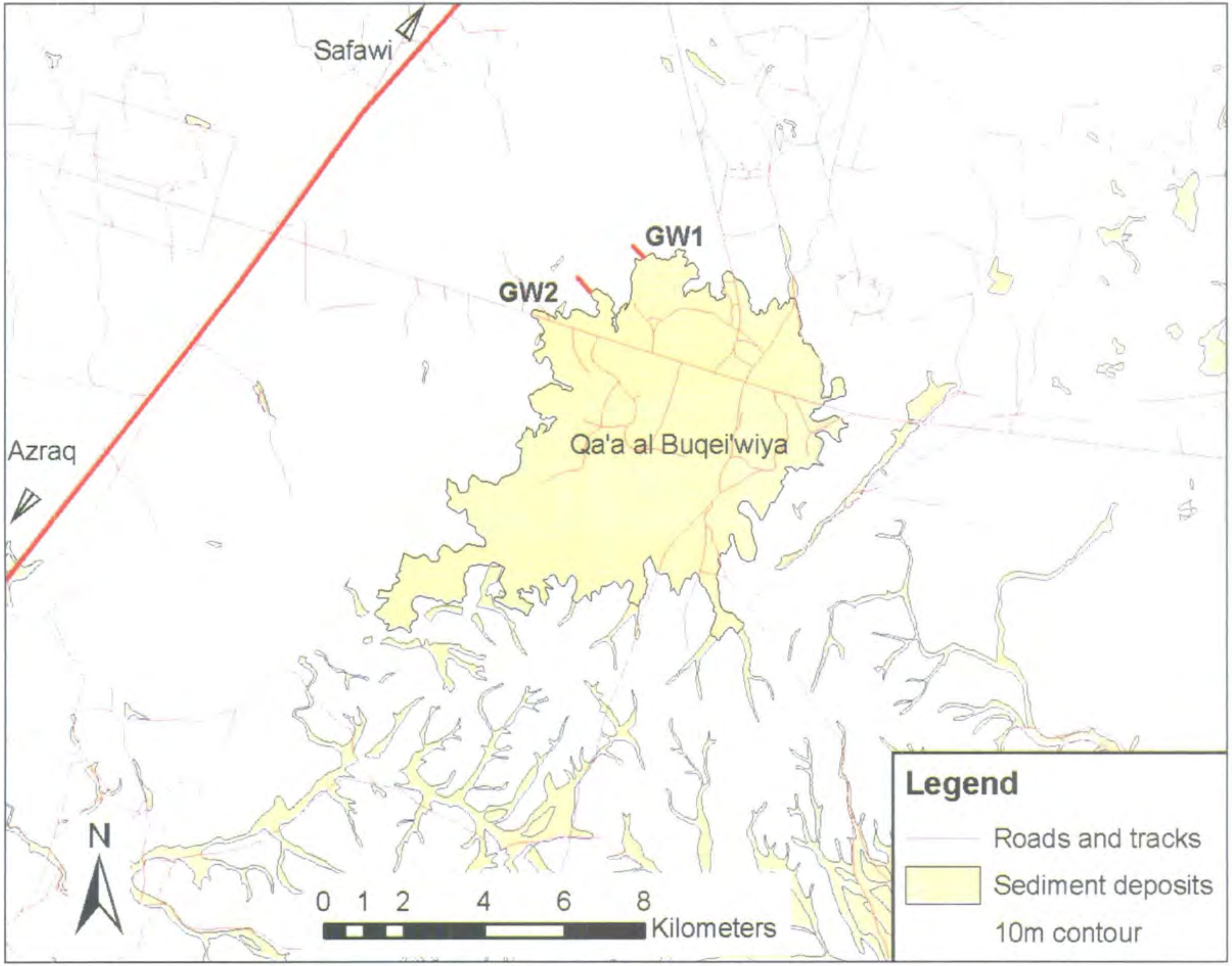


Figure 3.29 Location and extent of profiles GW1 and GW2 at Qa'a al Buqei'wiya

3.4.8 GW1 – site description

Profile GW1 is the only profile in this study located on Bishriyya basalt. The ground cover is characterized by typically rounded and well sorted clasts. The sediment surface is mantled in places by carbonate nodules, which at points form continuous pavement in between clasts. The profile crest is located on an exposed dyke of bedrock. The toe of the profile is located on the margin of the fine Qa'a sediment deposits (Plate 3.13). Organization in the clast surface is apparent (Plate 3.14). The profile is positioned in the northern corner of the Qa'a, in a relatively enclosed and sheltered location. The surface sediment exhibits a notable vesicular layer or horizon at points, especially around the margins and beneath surface clasts. Clasts are in parts faced with lichens which tend to be oriented to the north. The levels of ground disturbance in the area are low. The profile is relatively long and shallow (Figure 3.30) and is typical of the slopes on the Bishriyya basalt surrounding Qa'a Al Buqei'wiya.

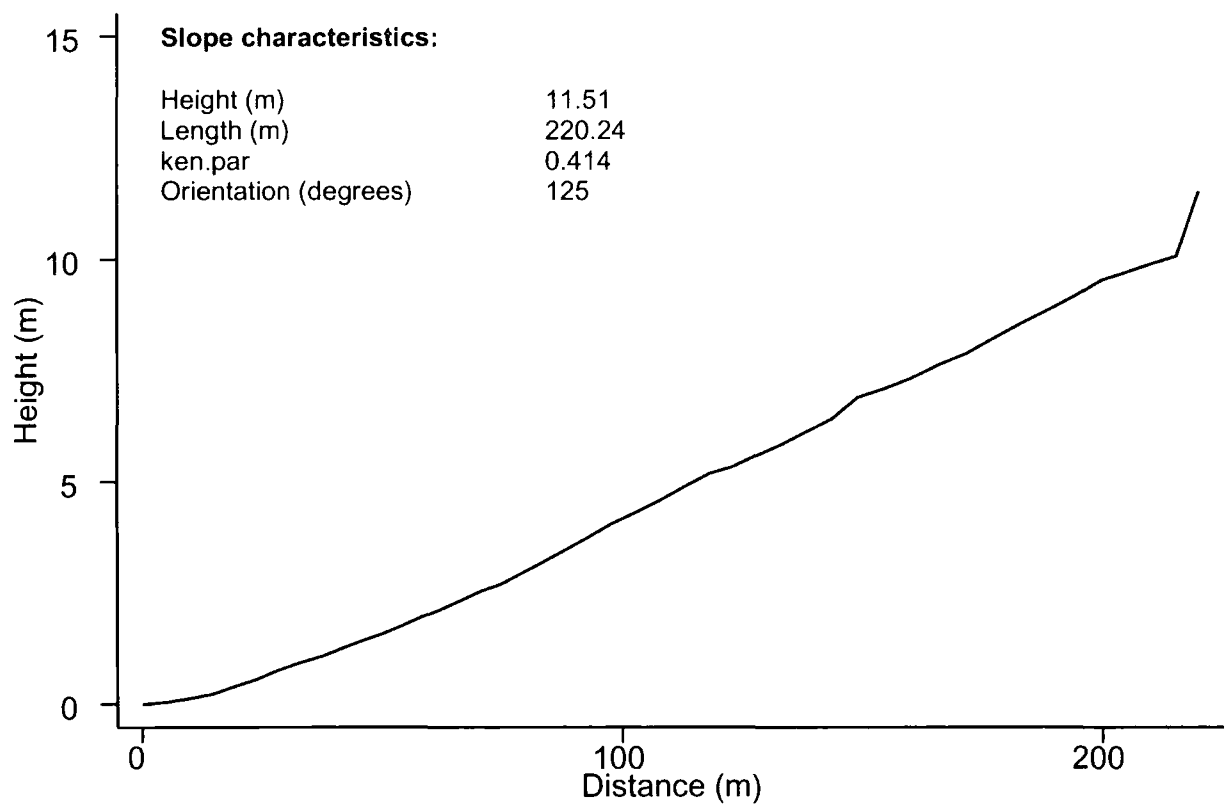


Figure 3.30 GW1 – Slope profile characteristics

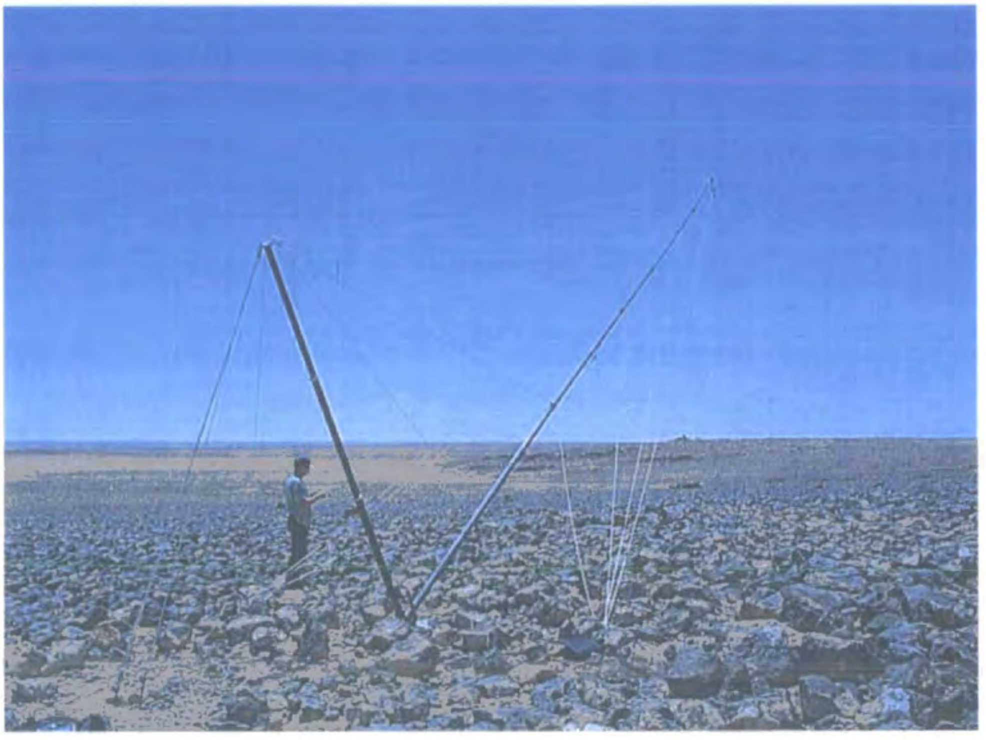


Plate 3.13 GW1 - Oblique photograph looking from the crest down the profile, with Qa'a Al Buqui'wiya in the distance. (Monopod camera boom in the foreground for scale)

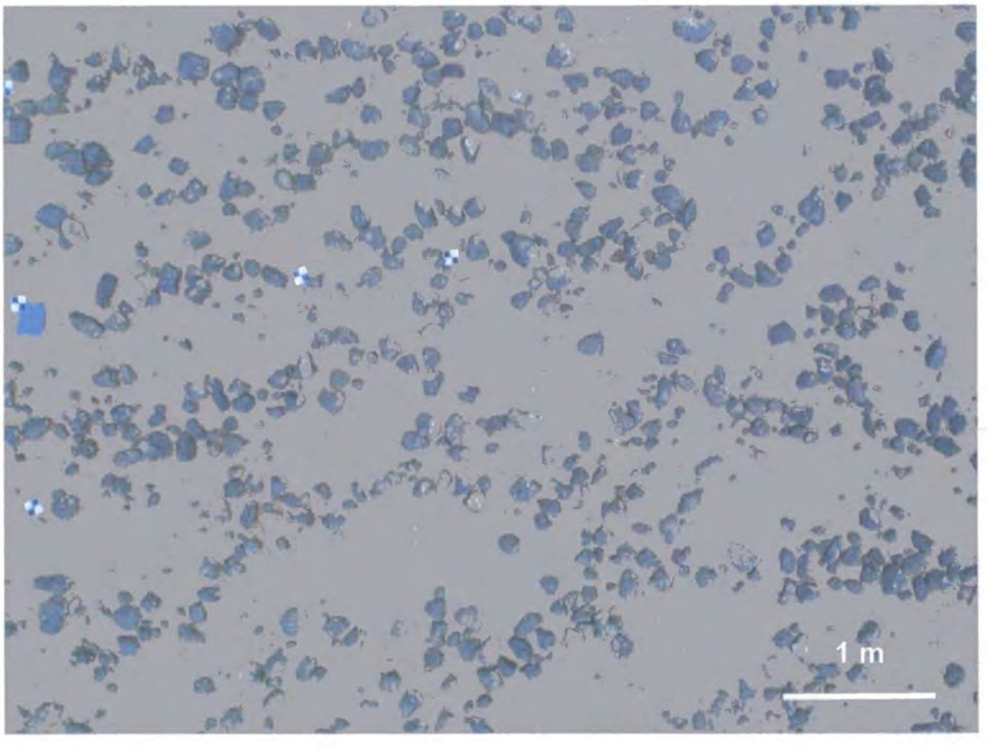


Plate 3.14 GW1 - Example of ground surface cover (GW1M). Of note is the distinctly non random clast distribution at the lower points of the slope profile

3.4.9 GW2 – site description

Profile GW2 is located on the Madhala basalt, which shows the greatest departure in surface form from the other surfaces previously described. The profile form tends to convexity (Figure 3.31). The surfaces appear to be dominated by a bi-modal distribution of surface clast sizes. Large clasts are interspersed by smaller fragments (Plate 3.16). The clasts are commonly faced with lichens, which are oriented to the north. Clasts are both angular and rounded and there is a clear variation in surface character from the crest to the bottom of the profile. The slope profile is located on the northern margin of the Qa'a. The profile crest is located on a bedrock outcrop and the toe is located on the edge of a wadi which feeds directly into Qa'a Al Buqei'wiya. The profile shows no evidence of ground disturbance (Plate 3.15, Plate 3.16).

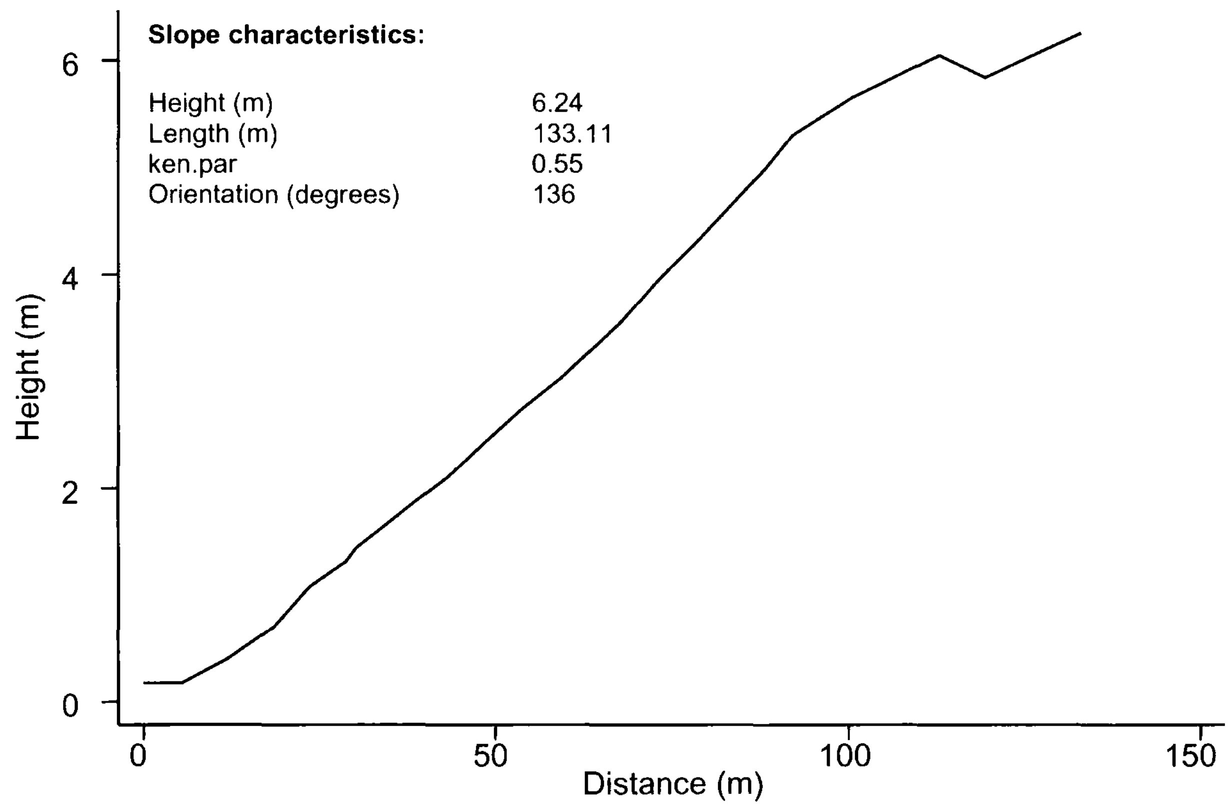


Figure 3.31 GW2 – Slope profile characteristics

Plate 3.15 GW2 - Oblique photograph of the toe of profile, monopod camera boom for scale

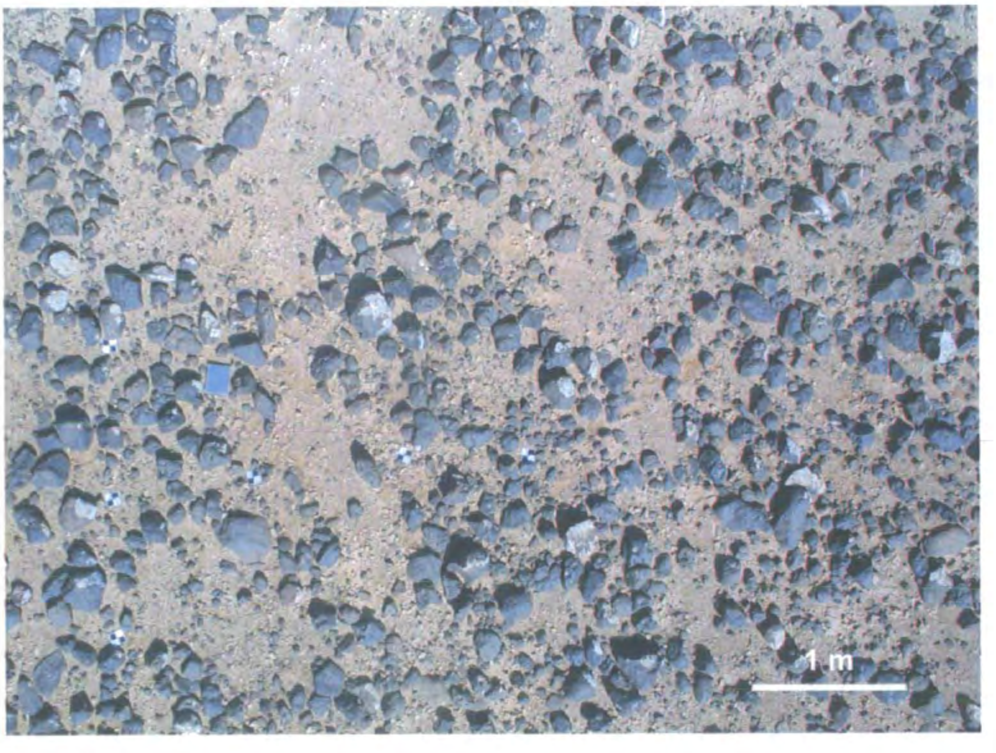


Plate 3.16 GW2 – Image showing an example of ground surface coverage (GW2M)

3.5 Conclusions

A semi-quantitative method of sample sites selection has been developed based on both previous work, field observations and a consideration of the issues of scale, location and adequacy. The need for a scaled approach to studying the surfaces of the Badia is important. Location is the dominant control on surface form. A method of systematically locating sample sites has therefore been developed. The method allows the results generated from the plots to be considered in the context of the wider geomorphological system of the northeastern Badia. The use of adequate methods of characterizing both the variations in surface form and the nature of surface processes within the sampling framework has been discussed. The sampling framework has been designed such that the scale of investigation at each level in the hierarchy is of relevance to the formative influence which dictates surface form.

Chapter 4: The characteristics of ground surface form

Chapter 4: The characteristics of ground surface form

4.1 Introduction

Links between surface form, slope process and landscape evolution on coarse clastic desert surfaces are poorly understood (Vincent and Sadah, 1995). Only by gaining a detailed and appropriate characterisation of contemporary form can links between form and process be explored further (Dunkerley, 1994). Attempts to characterize coarse clastic surfaces have produced a diverse and inconsistent range of methods and approaches (Poesen and Lavee, 1994). Adequate techniques of sampling and surface characterization vary between both the location and the purpose of the investigation (Dunkerley, 1995). The slopes of the northeastern Badia show a marked and systematic variation of ground surface cover has been related to slope form, geology and position in the landscape (Allison *et al.*, 2000).

The aim of this chapter is to characterise the variation in the surface geomorphology of the northeastern Badia. More specifically the analysis is designed to develop an understanding of the controls on the form of the boulder mantled surfaces, through an analysis of surface features which are indicative of process action. The influence of geology has previously been noted, but during the site selection a considerable variation in the nature of slope forms was noted (Chapter 3). The relative influence of slope form compared to the influence of geology is explored below. Finally, an assessment of the spatial character of surface clast organisation is discussed. This is designed to look at the spatial properties of structures on the surfaces, which in this context have only received very limited attention.

The aim of the chapter is further clarified by a series of objectives which form the structure for the discussion of results. The principal objectives are: to assess the nature of surface character indicative of modification by slope process action; to examine and differentiate the role of slope and geology on ground surface configuration; and to examine the spatial characteristics of the surfaces as an indicator of the nature of slope surface dynamics.

This chapter explores this variability further by developing a new image based technique for characterising the *in situ* nature of coarse clastic surfaces. The method develops highly detailed information on surface via a wide variety of variables. The technique developed operates at a level of measurement precision normally achieved at the plot scale (10^{-2} to 10^{1} m^2), but here applied to a large spatial area of the order of 50 m^2 is used. The results presented are generated from the seven profile sites, selected and described in Chapter 3.

4.2 Previous work

4.2.1 Work in the Badia

The nature of the surface clasts in the northeastern Badia is the clearest link between the geomorphology and the underlying geology (Allison *et al.*, 2000; Tansey *et al.*, 1996). Allison and Higgitt (1998) developed an assessment of ground surface cover which developed variables of direct relevance to surface processes, specifically slope hydrology. The method employed a measuring clasts in a 4 m^2 square quadrat if the intermediate axis exceeds 0.1 m. A quadrat base technique was favored above a grid-node sampling framework. The bias induced by the higher probability of larger clasts falling beneath grid nodes is of greater significance than the potential misrepresentation of small scale variability in surface character in the quadrat technique (Allison and Higgitt, 1998). Each clast was measured in major, minor and intermediate axis dimensions in addition to the length of the convex upper and lower clast perimeters, which were later used to derive clast burial approximations (Figure 4.1).

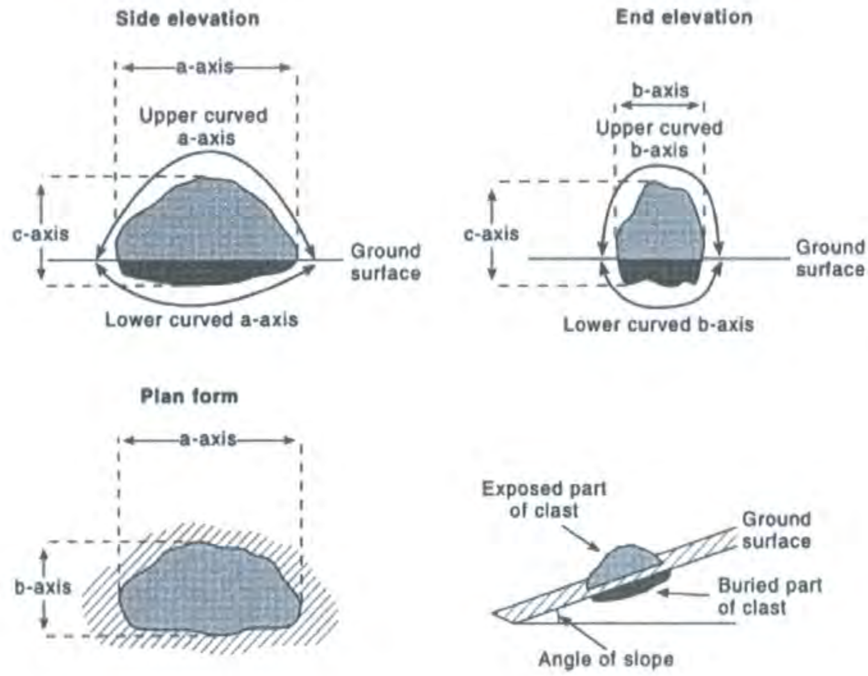


Figure 4.1 Measurements of surface clasts (after Allison and Higgitt, 1998)

The measures derived by the hand-counting method were used to equate averaged ground cover characteristics for the whole quadrat area, a widely used measure of clastic surface form. For example, an approximation to percentage ground cover was derived using an elliptical function to derive the surface area of each individual clast. The cumulative total estimates clast cover percentage (Higgitt and Allison, 1998, p. 174). The authors argue that this method generates a more precise measure of the actual percentage ground cover when compared to calculations derived from the mean clast size for the whole quadrat.

The approximation of variables, for example percentage ground surface cover, rests upon several assumptions of the clast and surface form. First, the surface area of the clast is assumed to be synonymous with the area of a planar surface projection of the major and intermediate axis. As such, the statistic assumes that all clasts reside in or on the sediment, with both the major and intermediate axis lying parallel to the ground surface. The degree to which this approximation corresponds to the actual planimetric ground surface cover has not been assessed, nor has the collinearity between clast burial and size and ground surface cover. Second, the contact perimeter, or clast edge length, which is a covariate of planimetric area, has been cited as a critical control on slope hydrology, providing a route for the exchange of gas and liquid between the sediment and surface (Poesen *et al.*, 1994). Under this characterization method the statistic assumes that clasts are buried to their maximum perimeter. For example, a perfectly spherical clast is assumed to be buried to exactly half of its diameter; its edge length is therefore equal to the circumference. Third, clasts are assumed to have perfectly elliptical form about their major and minor axis. From observation clasts in the Badia are frequently faceted and angular.

The implication of the assumptions of the hand-counting method mean that if the statistic is employed to relate surface form to hydrology, contact perimeters and their influence maybe overestimated where clasts stand proud of the sediment surface and have the converse effect where clasts are buried. The statistic may not be appropriate for examining surface hydrology or infiltration. The statistic is more applicable to examining sediment areas exposed to raindrop impact which is of importance in the open surface matrix of the northeastern Badia, but less useful for examining the role of clast-sediment contact perimeters on slope hydrology.

A wide range of results generated from quadrats at 5 plot positions on 25 profiles has been reported, and later summarized by Allison *et al.* (2000). The number of clasts recorded in each quadrat ranged from 13 to 151 with a mean of 67.8. This variation in clast number reflects both the underlying geology and relative position of the quadrat down the slope profile (Allison *et al.*, 2000). The extent to which the variability between plots reflects local heterogeneity in surface cover has not been assessed. Conceptual problems with the use of a quadrat to assess surface form variations are apparent. As slope length decreases the quadrat size approaches the length of the sampling interval between quadrats. Variability between quadrats may become masked though the relative size of the quadrat to the whole slope length is perhaps negligible on slopes as long as those described here. The previous technique employed a minimum clast size filter at 0.1 m intermediate axis, for ease and speed of data collection. There is substantial documented evidence of the importance of the finest fraction of the clast population (< 0.1 m intermediate axis) in controlling water partitioning between the surface and underlying sediments on coarse clastic surfaces (Poesen and Lavee, 1994). A more detailed resolution of characterization may be more appropriate for understanding the links between surface form and surface hydrology.

A final consideration is that of adequacy of the technique and type of statistics which are generated. The quadrat method is a destructive bulk sampling approach, and not an *in situ* assessment of surface form. It is the *in situ* character of the surface which influences and is influenced by formative process action. Measures based upon a bulk sample may not be useful or significant as a direct measure of the *in situ* character of the undisturbed surface. Work on similar surfaces beyond the Badia has used both bulk sampling techniques and aerial planimetry to generate an assessment of coarse clastic surface form.

4.2.2 Studies from beyond the Badia

Dunkerley (1996) identifies that, given the diverse influence of stone cover on surface process, little attention is commonly paid to the selection of appropriate methods for characterizing these surfaces relative to the objectives of the study. Two broad approaches to characterizing coarse clastic surfaces have been developed. The first bulk destructive sampling and the second, planimetric assessment of surface form.

The primary application of bulk sampling is to assess the absolute variation in clast size distribution between locations. Reviews of sampling procedures, for example Wolcott and Church (1991), Diplas and Fripp (1991) and Dunkerley (1994) highlight the problems associated with measurements and sampling procedures undertaken to quantify coarse sediment samples. Problems include the choice of process appropriate measures, the nature with which the sample location is positioned in space and the statistical significance of the sample taken. Comprehensive reviews of sampling coarse clastic materials which are beyond the scope of this study are provided by Church *et al.* (1987), Wolcott and Church (1991), Gale and Hoare (1992) and Dunkerley (1994, 1995). Sample size, or number of clasts is commonly regarded as the main limitation in experimental design for bulk sampling coarse sediments. Dunkerley (1995) argues that the nature of the clast size distribution around the mean value is of far greater value than the central tendency of the clasts size distribution. It remains to be seen whether it is the statistical significance of the number of clasts in a sample, or the aerial extent of the surface characterized which dictates the sample size required in the northeastern Badia.

Dunkerley (1994) argues in a study of rocky dryland surfaces that considerations of statistical bias must be considered in sample collection. Dunkerley (1994) highlights the debates surrounding the over-representation of the coarsest fraction of a sediment sample if sampled using the grid node intersection technique, later adopted by Higgitt and Allison (1998). Conversion criteria to correct this error have been discussed by Kellerhals and Bray (1971), Diplas and Fripp (1992), and Church *et al.* (1987). Dunkerley (1995) argues that the bias is not a constant within a data set, as it varies with the character of the sample population. Topographically controlled variation in rock surface cover, as demonstrated by Allison *et al.* (2001) in the northeastern Badia and Brown and Dunkerley (1996) at Fowlers Gap, Australia, and the work of Vincent and Sadah (1995a, 1995b, 1996a, 1996b) in Saudi Arabia, may be masked by the bias incurred by the sampling technique. An adequate bias correction should be applied which is specific to the surface in question. The power of inferential statistics increases with sample size, but simply collecting a larger sample is logistically difficult (Wolcott and Church, 1990). Wolman

(1954) suggests that samples greater than 100 kg are needed to gain statistical significance. Additionally, there is the issue of sample availability. Can a large enough number of clasts be collected in an aerial radius that is small enough to be considered homogenous (Dunkerley, 1994)?

To overcome the effects of sample misrepresentation techniques that do not rely on full size distributions of sediments have been developed. This commonly involves sampling the coarse fraction of the whole sample. For example, Bradley *et al.* (1972) used a constant search method, whereby all stones collected within a twenty minute period were measured and then the 50 largest averaged to represent the coarseness of bed material, similar to a random walk strategy (Wohl *et al.*, 1996). Random walk methods usually produce repeatable if not accurate results. The variability of result is consistent and hence negligible (Wohl *et al.*, 1996). Again, by sub-sampling much of the detail in the data which may provide a valuable measure of surface form is lost. In the case of the northeastern Badia, where surface variability is very subtle the use of such a sampling technique may not be suitable to identify systematic surface variability. Melton (1965), in a study of debris covered hillslopes in Arizona employed semi-quantitative surface characterization criteria. A measure of the clast intermediate axis was accompanied by a five class description of roundness, lithology, the degree of chemical weathering, degree of cementing by caliche and burial. Samples were collected from the steepest parts of the slopes and points located by an undefined procedure termed 'randomisation'. On surfaces such as those of the northeastern Badia where variability in form is so slight a qualitative method of characterisation may not able to differential between sites.

There is a paucity of work within semi-arid slope hydrology which has examined the role of the spatial clast distribution on hydraulics and sediment dynamics. Jean *et al.* (2000) and work from the study of bluff bodies in boundary layer theory and hydraulics, for example Schitchling (1955), are the only studies where this is considered in a quantitative manner. The spatial distribution of clasts is often only mentioned briefly (Abrahams and Parsons, 1994), and observations are not commonly substantiated. A more favored approach to characterizing the surfaces remains the simplistic mean percentage clast cover or intermediate axis dimensions (Bunte and Poesen, 1993). In the northeastern Badia where surface clasts are pose prominent individual obstacles to slope processes a consideration of the spatial character of the surface may be beneficial. Additionally, a marked degree of surface organization and structure has been observed. Spatial arrangement of clasts is therefore an important consideration.

The second technique of surface characterization, the planimetric *in situ* form, has been adopted less widely than the bulk sampling approach. Several studies have examined the undisturbed *in situ* character of surfaces, particularly in respect to surface and slope evolution. Friend *et al.* (2000), in a study of boulder-dominated colluvial slopes, employs measures of size (major axis), clast volume (undefined), elongation (intermediate : minor axis ratio), angularity (qualitative), to link geological age to surface cover character. Friend *et al.* (2000) also uses macro-fabric analysis to generate Eigenvalues which identify the alignment and arrangement effects of slope processes, but with little success. The clast-supported structure of the boulder mantled slopes studied inhibits boulder realignment by slope process action. The weak statistics returned are perhaps not surprising. Eignenvalue analysis may however be more applicable on surfaces where between-clast contacts are minimal, freely allowing realignment, as potentially occurs in the northeastern Badia. Ibbeken *et al.* (1998) show clast orientation to be a strong indicator of alluvial fan development at Hanaupah Fan, Death Valley. Additionally, clast position and titling has been linked to rates of geomorphic activity on clastic desert surfaces by Sena *et al.* (1994).

The dearth of literature that has addressed relative spatial position is not surprising. On rock fragment dominated surfaces the distinction between what is, and what isn't a clast, is less clear than in the northeastern Badia. At the catchment scale ground surface cover maybe considered to be homogenous as the nature of variation maybe insignificant as an influence of catchment hydrology. The spatial distribution of clasts on rock fragment surfaces may not be of great importance in dictating flow hydraulics, where finer, less distinct fragments dominate. The surfaces of the northeastern Badia represent a much greater polarity in particle sizes. Boulders (clasts) are relatively massive compared to the unstructured underlying silt clay sediments (Allison *et al.*, 2001). The position and organization of clasts in the open surface matrix may be of more significance on these surfaces as a control on overland flow hydraulics.

The *in situ* form of coarse clastic semi-arid surfaces has received some attention. An aerial, synoptic or planimetric representation of landforms has benefits for morphometry, monitoring and modelling in geomorphology. Planimetric assessments of coarse clastic materials have been developed to approximate clast size distributions (Macloed, *in press*; Dunkerley, 1994). Clast planimetry assessments are scale independent and can be applied from the microscopic to the macroscopic (Kellerhals *et al.*, 1975). The approach conventionally uses a scaled aerial photograph or sketch diagram of the surface from which measurements are derived and as such the technique is non-destructive. The technique only measures the exposed portion of the *in situ* clast, an assessment which may yield a more appropriate characterization of the surface relative to slope process action. On surfaces with a distinct polarity in clasts sizes between the underlying fines and the surface clasts, as in the northeastern Badia, a planimetric view is able to differentiate the characteristics of the surface which act as obstacles to slope flow processes. Edge lengths, clast size and percentage ground surface cover are seen as critical controls on surface processes (Poesen and Lavee, 1994).

Examples of planimetric approaches to coarse clastic surface assessments are numerous (Dunkerley, 1995; Church *et al.*, 1987; Al-Farraj and Harvey, 2000). Dunkerley (1995) employed aerial photographs of rock covered surfaces to examine the granulometry of various clastic surfaces. The commonly heavily skewed nature of particle size distribution is suggested to have a profound influence and control over behavior at the surface (Dunkerley, 1996). Sorting and clast population structure are critical. Ibbeken *et al.* (1998) adopt a photo-sieving technique based on digitized photographs obtained from 3 m height, vertically above the surface. Fourier analysis was used to assess the clast size parameters but no attempt was made to compare the results generated to those derived from mechanical sieving techniques. Al-Farraj and Harvey, (2000), in a study of desert pavement surface terrace and fan surfaces in Oman and UEA, developed a semi-qualitative characterization technique for classifying pavement characteristics. Variables include the degree of pavement development, clast sorting, relative clast size, clast shape, fracturing of clast and surface texture. Oblique photographs of 1 m^2 plots were used to derive the overall particle size range, by point sampling at 100 intervals, in addition to axis and roundness measurements of the 25 largest clasts within the plot. Al-Farraj and Harvey, (2000) recognise the limitations of the technique in assessing conventional descriptive statistics of particles size distributions due to camera distortion and the effects of clast burial, but highlight the value to assessing the nature of the relative changes between sites (Al-Farraj and Harvey, 2000).

A second stream of research has developed the use of automated image analysis to assess grain size distributions but none have been undertaken on photography of undisturbed arid clastic surfaces. Two dimensional image analysis is based on a planimetric projection of particles derives statistics on clast perimeter, dimensions, texture and area. Examples include Wunsam and Bowman, (2001) and Cheng *et al.* (2000). Comparisons with conventional sieving techniques have been undertaken by Fernlund (1998) Bozdag and Karpuz (1997) and Dunkerley (1995). Techniques applied directly to geomorphological applications tend to use manually digitised binary overlays of conventional film photography (Dunkerley, 1995; Diepenbroek *et al.*, 1992), which is both time consuming and looses precision of measurement.

4.2.3 Recommendations for experimental design

A planimetric assessment of surface form appears the most appropriate approach to studying the slopes of the northeastern Badia. The specific geomorphology of the northeastern Badia lends itself to this approach in several ways. First, the clasts present themselves as spatially distinct elements on the surface. Their colour, spacing and size enable them to be clearly distinguished from the sediment surface in-between and below. Differentiating between individual clasts and the sediments should be easy. Second, evidence that the surfaces experience overland flow is a key component of contemporary and potentially previous surface conditions. The planimetric perspective is an ideal viewpoint from which to assess *in situ* process-specific surface characteristics. Spatial heterogeneity and surface microtopography have been cited as important controls on both process action and influence. The spatial extent of the area of the surface in consideration is therefore important. Sample size in previous studies is highly variable between plots. Consideration of a larger number of clasts would ensure the statistical significance of clast size distribution from all plots. The nature of variability between distal and proximal sites is slight. Therefore the resolution of sampling and measurement is vital to bolster the stability of the data generated. Weak correlations between previously measured variables imply that a greater range of more appropriate measures of the surface would be beneficial. Third, previous techniques are predominantly destructive. The geometry of distinct surface clasts and their specific influence on both hydraulics and hydrology has received little attention at the slope scale. A non-destructive technique would in addition allow repeat measurements and hence monitoring of the surfaces through time and between field successive field experiments.

4.3 Design of surface characterization technique

The requirement for the surface characterization technique stipulates both an extensive sample, in terms of aerial cover and statistical significance, and a high precision of measurement such that small clasts size fraction can be considered. The technique described below aims to combine a planimetric assessment of the *in situ* surface character using low altitude high resolution aerial digital imagery, combined with an automated analysis procedure. The technique is described below in three parts, image capture, image processing and data analysis.

4.3.1 Image capture

The aerial extent of the sample or image is determined by the presence of structured microtopography in the northeastern Badia. Step-like features have been observed (Higgitt and Allison, 1999a) which appear to coalesce and tessellate to form polygonal structures. A consideration of the structure wavelength, discussed previously with reference to the Nyquist frequency (Chapter 3), is used here as the minimum extent of the sample size. Observations in the field suggest that the dimensions of structures are never greater than 1.5 m by 2.0 m of continuous width. A sample area with a width of at least 4 m exceeds the recommendation of the Nyquist frequency in this context, such that the area contained within the sample can be considered homogenous. The image capture technique developed below uses an image of ratio of 6 : 4 width to height, so sample width and height should always exceed 4 m.

The camera altitude dictates the aerial cover of the sample. The method developed below allows the camera to be held at altitudes of between 2 and 120 m. The precision of data collected is therefore a function of the resolution of the camera. An ideal level in precision of measurement was selected. Previous work in the northeastern Badia rounded measurements to the nearest 0.01 m, so a precision equivalent or in excess of this is desired. A simple laboratory experiment shows the equivalent ground dimension of the image pixels with increasing camera height is expressed by `camera height = 1233.3 × pixel width + 1.632` (r^2 = 0.999). This relationship determines the height from which suitable images can be captured, such that individual clasts can be identified and differentiated. A linear relationship between image area and camera height is expressed by `camera height = 0.0922 × image area + 4.376` (r^2 = 0.987). This relationship is used to determine the optimum altitude for image capture. A height of 12 m was selected as this returned an image of over 6 m by 9 m, whilst maintaining a pixel dimension on the ground of less than 0.01 m, returning measurements of clasts to within 99 % of their actual dimensions, measured by calipers.

High altitude images were captured from 120 m for each site to establish the continuity of ground cover and to identify features not apparent from the ground, such as lineations, geological anomalies and bedrock outcrops which were employed in the site selection procedure described in Chapter 3. Examples of both the 12 m and 100 m altitude images demonstrate the range of camera altitudes achievable (Plate 4.1). The 12 m image demonstrates the clarity of the images obtained using this technique. The contrast between the surface clasts and the sediments is notable with a high resolution and large aerial cover. The technique is flexible in that the equipment can be maneuvered across the surfaces whilst capturing images with only two field operatives. The captured image file format can be imported directly into standard Microsoft Windows™ based image analysis package for processing, without the need for developing or scanning. This can be undertaken in the field. 12 m altitude images were captured at the Top, Upper, Middle, Lower and Bottom plots.

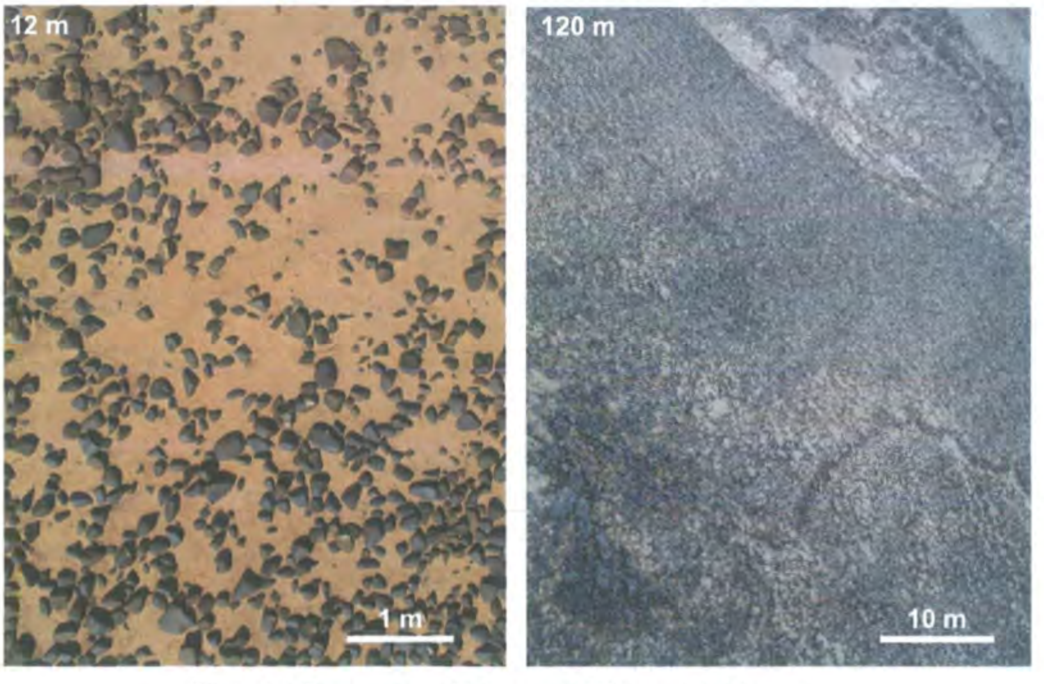


Plate 4.1 Examples of 12 m and 120 m aerial images

Recent developments in digital camera technology have resulted in digital image quality approaching that of film based photography at minimal cost. Digital imaging has the advantage of instant picture viewing after capture and has effectively no limit on the number of pictures that can be captured. The choice of digital camera was made on the basis of charged couple device (CCD) resolution, which dictates the resolution of the final images, lens quality and colour accuracy, which controls the quality of the image, software support and cost. The Kodak DC range of commercially available digital cameras has camera mounting software that enables fully functional remote control of all camera features, via serial connection to a remote laptop. The laptop enables real time viewing of captured imagery allowing targeting and brightness corrections to be undertaken in the field. The use of NickelMetal Hydride batteries and 128 Mb CompactFlash™ memory cards means that the selected camera can be used for a full day in the field, collecting over 100 maximum resolution images.

The camera finally chosen was a Kodak DC240 Zoom, and later a ruggedized Kodak DC5000. The DC240 has a sensor resolution of 1344 x 971 pixels, with the maximum image resolution of 1280 x 960 pixels, in 24-bit colour (Shortis and Beyer, 1996). In a comparison of three Kodak digital cameras of varying price and resolution, Ahmed and Chandler (1999) noted the surprisingly favourable results returned from the cheapest 'off the shelf' lower resolution Kodak DC40 digital camera (0.38 million pixels), when compared to the more conventional reflex camera bodied Kodak DCS420 and DCS460 (1.5 million and 6 million pixels, respectively), more commonly used for photogrammetry. The DC240 and DC5000 return similarly favourable results (Shortis and Beyer, 1996).

Although a photogrammetric camera calibration is beyond the scope of this investigation, its importance is recognised. Ideally a full photogrammetric calibration of the internal camera geometry would be undertaken, as described by Chandler and Padfield (1996), but the levels of precision required for this study do not justify this (Ahmed and Chandler, 1996). The more simplistic ISO 12233 camera resolution and imaging accuracy tests (VFA) using the DC240 show minimal geometric distortion at either the wide or the telephoto end of the lens (Plate 4.2a, b), and high visual resolution for high contrast objects (Plate 4.2c), and accurate clean and well saturated colour preservation (Plate 4.2). Radial lens distortion is cited in Ahmed and Chandler (1999) as significant for all three cameras assessed, with the most severe displacement on the image fringe. A 39 mm zoom is used here to minimise this radial image distortion. The images used within this study were then cropped to 85% of their width and height to eliminate the most significantly distorted areas of the image.

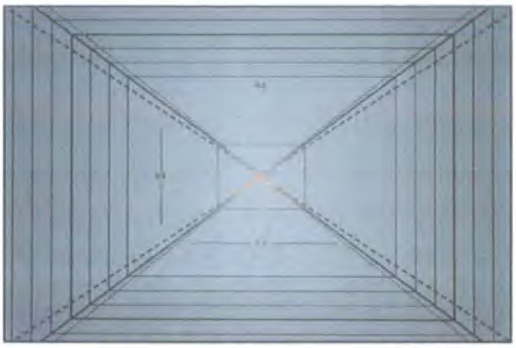
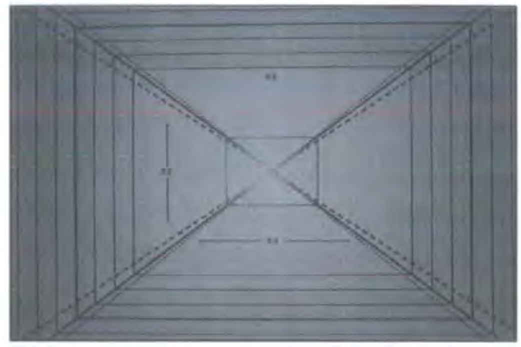
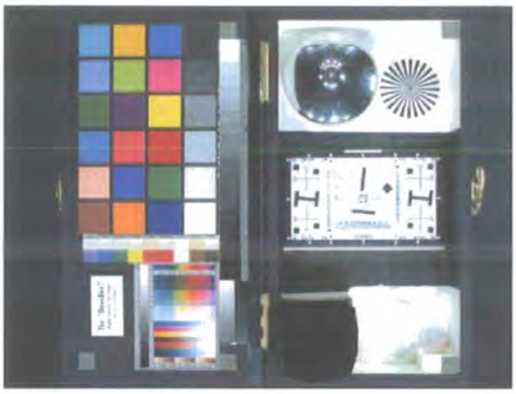
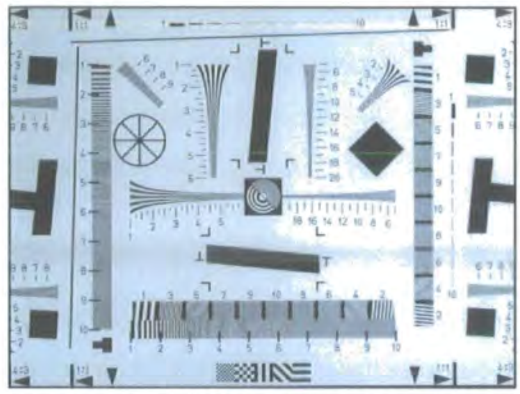
 (a) Viewfinder accuracy/flash uniformity target (VFA) (Wide angle)	 (b) Viewfinder accuracy/flash uniformity target (VFA) (Telephoto)
 (c) Colour target	 (d) ISO 12233 ("WG-18") resolution target

Plate 4.2 Camera calibration chart for DC240[*]

The lens has an aperture of F / 2.8, and focal length equivalent to 39 to 117 mm. The weight of the camera with batteries is 0.35 kg. The requirement for the camera to be of the order of 10 to 15 m above the ground is a relatively unexplored altitude that resides below conventional aircraft based aerial but above ground based photography. Three techniques were employed to hold the camera at this height, with a mixed range of success. First, a 13 m carbon fiber camera boom, named a 'Monopod', was deployed (Plate 4.3). This system returned very favorable results. The boom was able to lift the camera to a height of over 10 m, without obscuring the image. The system was very stable in low winds and could be transported and erected by two field operatives at each site in less than half an hour. Consistency in altitude and image area between sites was easy to obtain with this method. A high degree of control over altitude was found to be beneficial during the calibration stage of the technique development. Images could be sampled at precise 1 m intervals, up to 10 m. There are several disadvantages of using the boom system. Image capture was undertaken as close to midday as possible to reduce the effects of oblique shadowing on the surfaces. During this period the boom cast a shadow across the image.

[*] http://www.imaging-resource.com/PRODS/DC240/240PICS.HTM

The shadowing was later found to be problematic in the image analysis, but could be later removed with for example Paint Shop Pro™. It is difficult to prevent the vast array of cables and wires that support the boom from becoming entangled on the boulders during transportation. Walking across the area to be photographed during the set-up procedure also potentially disturbs the boulder surface. The monopod requires five solid ground anchor points to hold the boom to the ground. On sites where sediments are thin, weak or hardened, establishing a reliable ground fixing is found to be difficult. Flexibility and time is the systems downfall. The apparatus has to be dismantled entirely between plots, meaning that one slope of five plots would take one day to photograph, which is a similar time to the hand counting technique previously used.

Plate 4.3 Monopod camera boom at Marab Swayed

The latter two methods used the same principle of hoisting the camera. A helium balloon and an aerofoil kite are found to provide a stable camera platform. A 2 m diameter helium ball, tethered to a fixed ground point was employed in the northeastern Badia. The balloon provides approximately 2.5 kg of vertical lift and is capable of holding the camera at a range of altitudes that is only limited by the cable length, which in this instance is 125 m. A helium blimp was chosen in preference to a hot air balloon due to size limitations (Aber *et al.*, 2002). UK aviation laws restrict the maximum size of unlicensed tethered aircraft; calculations suggest that a balloon capable of supporting the payload of the digital camera work exceed the legal size limit as defined by Air Navigation Order 1989 (Statutory Instrument No 1989 / 2004) and the Rules of the Air Regulations 1991 (Statutory

Instrument No 1991 / 243 7). The benefits of the balloon system were the reduced shadow cast on the ground surface which was invisible on the majority of images and the flexibility of movement. The range of heights allows ground cover of up to 40000 m^2 from an altitude of 100 m, in addition to a high degree of control at low levels. The balloon faired less well in moderate to high winds as the lift was low relative to the lateral forces on the helium sphere exerted by the wind. The sharp boulder surface was also not welcoming to the delicate balloon membrane. Additionally three field operatives were required to fill the balloon and position the camera above the plot locations.

The final and most successful method of supporting the camera was found to be an aerofoil kite. Increasing enthusiasm for KAP (kite aerial photography) provides a large resource base on the design and operation of a kite based aerial photography (Benton, 2001 - 2002). A Stratascoop III, constructed by Greens Kites of Burnley, UK, was employed due to its high flying angle and infamous lifting force, controlled by a single 250 kg breaking strength nylon cord. This kite is capable of flying in a wide range of wind speeds and provides a stable, vibration free platform. The kite can easily be operated by two field operatives enabling walking across rough terrain whilst capturing images. Limitations of this method are primarily related to the consistency and strength of wind. Low wind conditions of below 5 km hr^{-1} do not provide adequate lift, and conversely high wind conditions generate excessive lift.

The balloon and kite techniques employed the same method of attaching the camera to the kite line. The camera was supported in a Picavet cradle (Picavet, 1912). The cradle was attached 25 m below the kite on the line, such that the kite was always at least 25 m from the ground and above turbulent air (Figure 4.2). This also has the effect of reducing the angle of the kite line between the operator and the camera, minimizing the possibility of image obstruction by either operator or cable. The Picavet cradle holds the axis of the camera vertical, irrespective of the angle of the tether line, counteracts rotation and acts to dampen vibration. Ballast was fixed to the cradle to adjust the camera axis normal to the local slope angle. The camera was controlled directly from the ground via a 125 m serial cable connection to a laptop. The functionality of the camera enables reviewing of captured images by the operator, such that the camera can be precisely located above a desired position. Images were viewed as captured to ensure quality and position. Images were saved to the hard disk of the laptop in Tagged Image File Format (.tif), with minimal compression to maximize image quality.

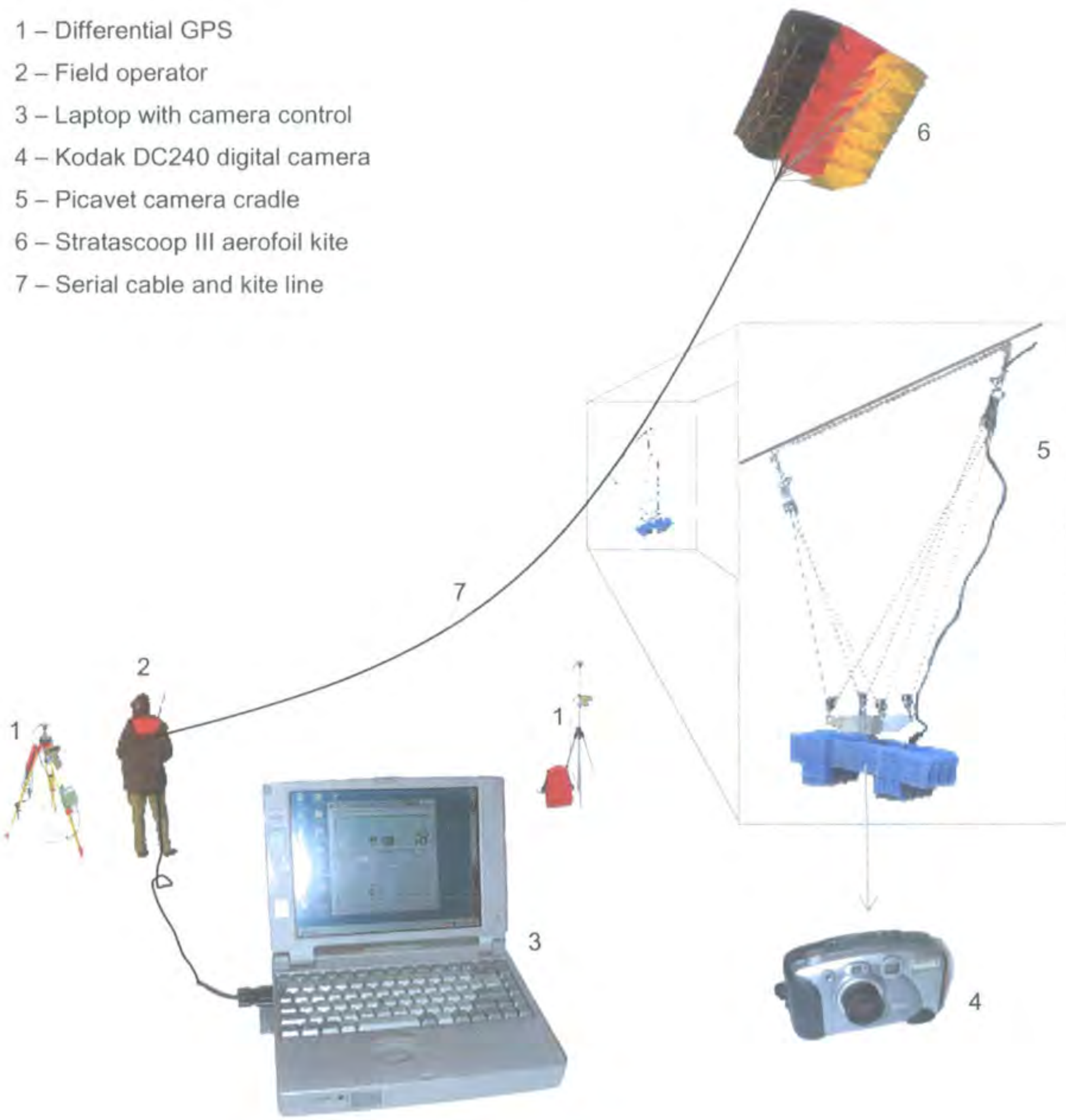


Figure 4.2 Image capture apparatus

Image location and scale calibration was achieved in the field with differential GPS (DGPS) surveying of ground control points, which were visible in the captured images in the real time view on the laptop. Under favorable satellite availability, the DGPS was found to return accuracies in the order of 0.02 m in x and y axis, from a 3 epoch Time Tagged Point position (Leica, 1997). Photogrammetric ground markers where fixed to the sediment surface within the area of the image. A distribution of at least 10 markers was used in each image to identify position, orientation and contour directions. The positions derived were then used to scale the images and position them in the field area during the image processing procedure within ArcGIS 8.1. Images were always scaled using ground markers rather than estimations of camera height for increased accuracy. Cropped and geo-corrected images were imported directly into the image processing.

4.3.2 Image processing

The image processing technique measures the planimetric extent of the exposed clast from a aerial perspective. Clasts are identified as individual objects from which appropriate measurements can be derived. The colour and contrast of the surfaces suggests that the most fruitful method of analysis would be based on analysis of binary data. For each pixel within the image it can be considered either to represent a clast or sediment within a binary overlay (FFA, 2000) The chosen software must be able to perform image processing and thresholding on colour intensities, such that rock and sediment can be differentiated. The selection of software was also based of its ability to generated appropriate statistics. The majority of commercially available image analysis software is aimed purely at deriving size and population distributions of objects and therefore treat objects as individuals whose juxtaposition is not of importance. An assessment of *in situ* surface form requires this spatial data.

PC_Image, produced by Foster Findlay and Associates, UK, was found to be the most suitable package for this purpose. The software is capable of importing images directly and enables significant control on filters and measurements by the user. Results are exported directly into a .dat format which can be imported to a statistics package such as Stata or SPSS. The image analysis procedure followed a sequence of steps that was applied to each captured image (Figure 4.3). The analysis procedure is split into four sections; image calibration, image enhancement, binary processing and finally object measurement.

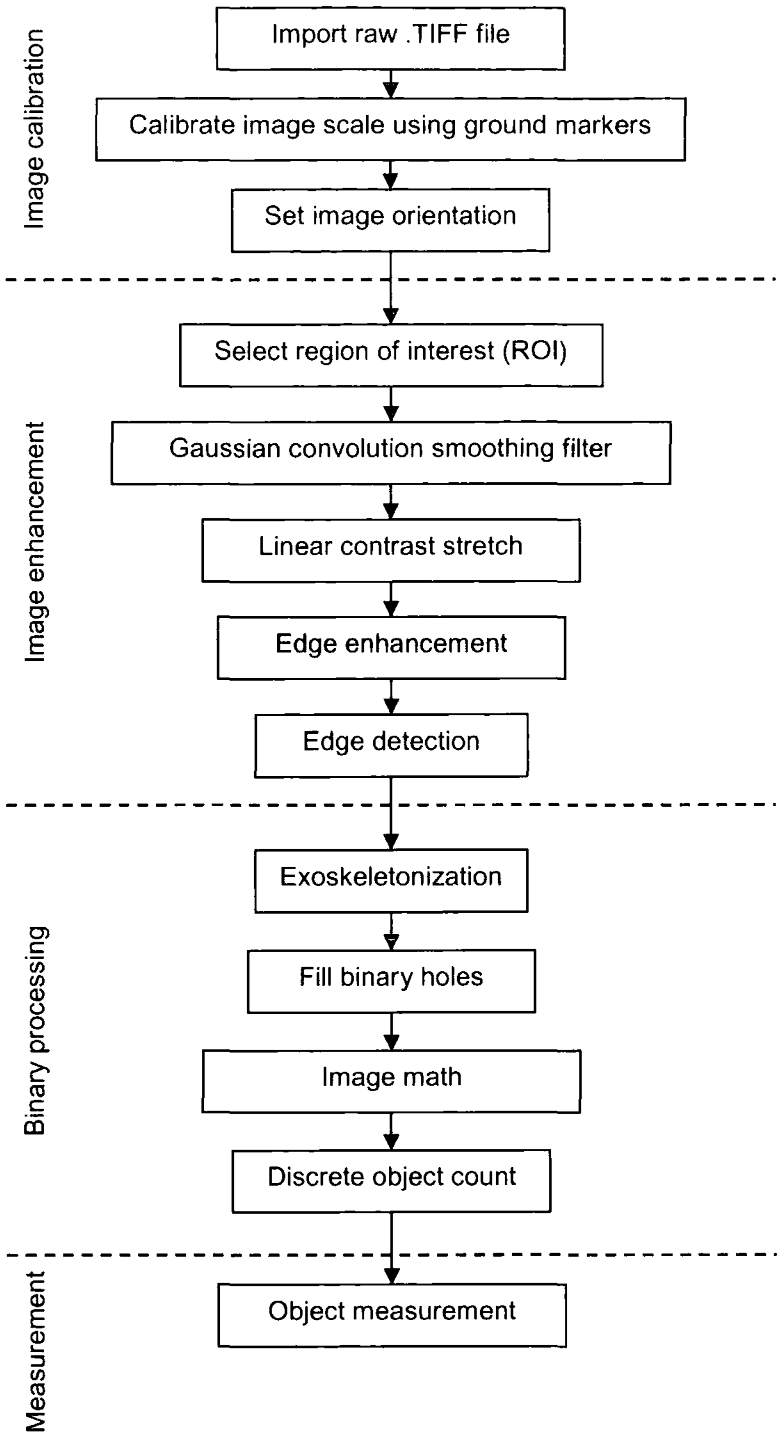


Figure 4.3 Image analysis procedure

Image calibration rescales the image using the photogrammetric ground markers within the captured image. Known distances between the 10 photogrammetric markers were input into PC_Image, from which a ratio of pixel width to meters is calculated. Subsequently all measurements taken from the image are in meter units. The image is rotated relative to slope, such that down-slope is set at 0°, again using the photogrammetric ground markers.

The second stage of the procedure optimises the colour and brightness distribution of the image to aid in the separation of clasts. A region of interest (ROI) is drawn as a rectangle with 85 % of the images width and height, centred on the image center point. By only assessing the area contained within the ROI the effects of radial distortion around the image edge are minimized (Ahmed and Chandler, 1996). Two filters are used on the image to enhance the differentiation between the sediments and clasts. First, a Gaussian convolution smoothing filter was passed over the image (Gonzalez and Woods, 1992). The Gaussian filter has the effect of blurring and removing noise from the image, without loosing the clarity of the object edges. On the Badia surfaces a Gaussian convolution tends to smooth shadows and surface pitting texture between opposed boulder faces and acts to reduce the presence of lichens on boulders and granular textures on the sediment surfaces, further differentiating between clasts and sediments (Figure 4.3). A disadvantage is that small mono-pixel clasts may be lost, but no meaningful measures can be derived from objects of this size.

The second type of filter employed is a non-linear Sobel edge detection filter (Gonzalez and Woods, 1992). The filter acts to sharpen the boundaries between sediments and clasts. The filter is constructed from kernel of 3 x 3 pixels and hence operates over a small area of the image at a time (cropped image area is 1088 x 816 pixel). The filter is as a result not affected by gradual changes in grey level intensity across the image inferred by lighting differences. Only local edge data rather than wider scale trends in the image are enhanced. The effect of this filter on the Badia images is the development of distinct boundaries between clast and sediments, in addition to further smoothing colour and texture with clasts and sediments (Figure 4.4). This filter acts to make both the clasts and the sediment exhibit a more uniform colour spectrum, easing their separation.

After filtering, a linear contrast stretch is performed on the image which enhances the colour difference between the dark boulders and the relatively light sediments (Figure 4.4). The contrast stretch was found to identify the underlying sediments in a tightly constricted spike at the high end of the color spectrum, representing a lighter coloration. The distinction of sediment color is more tightly constricted color distribution than the clasts. Clasts are multifaceted, clad with lichen and often shadowed, explaining the increased range of color. Once a characteristic sediment color spectrum has been identified, all other areas of the surface cover can be considered to be clasts.

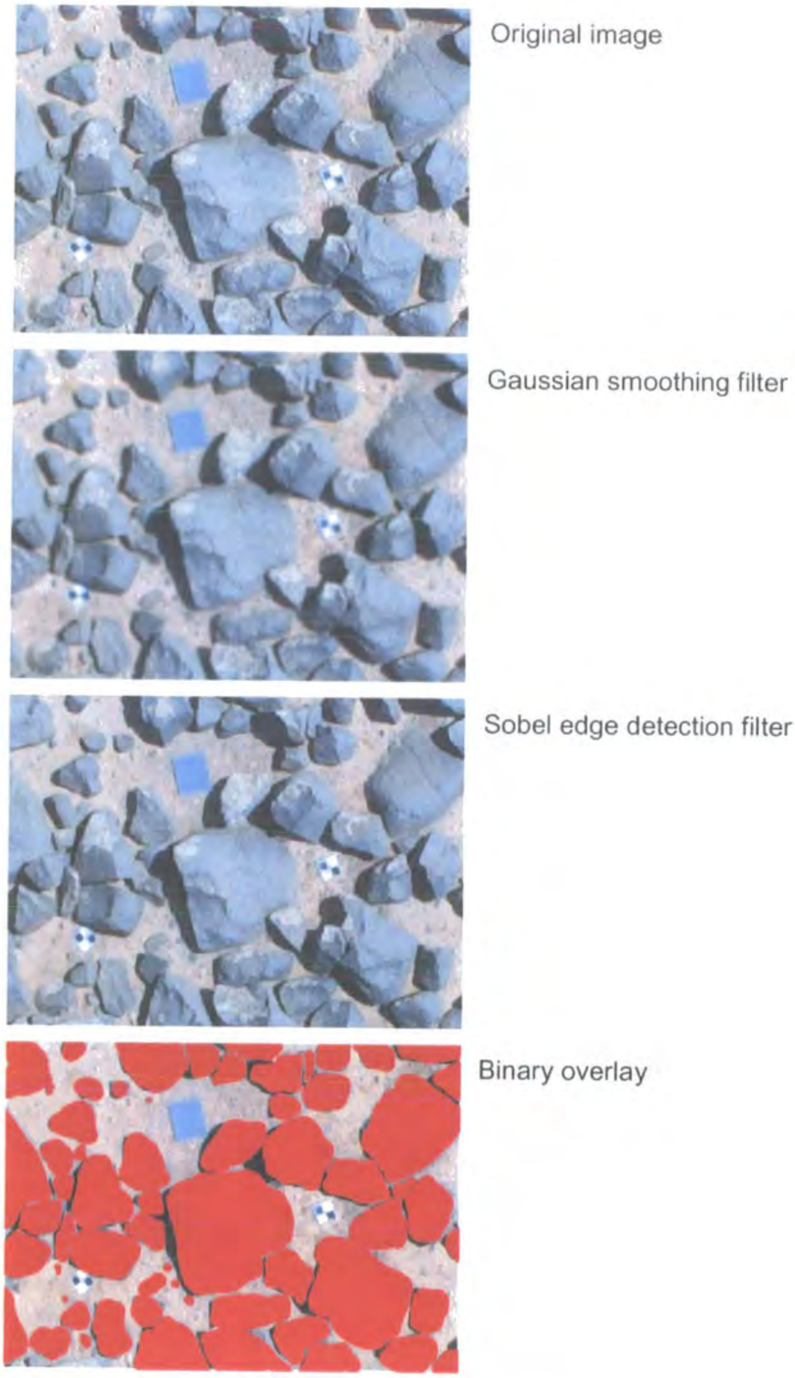


Figure 4.4 Sample results from image processing

The distinction between clasts and sediments on the image is identified statistically using a thresholding procedure based on a triangulation algorithm (FFA, 2000) (Figure 4.5). A line between the maximum frequency of grey levels (b_{max}) and minimum frequency of grey levels (b_{min}) is constructed. The distance between the line and the histogram (b) is calculated for all values between b_{max} and b_{max}. The point at which b_{max} intersects the histogram is the threshold value (b_o).

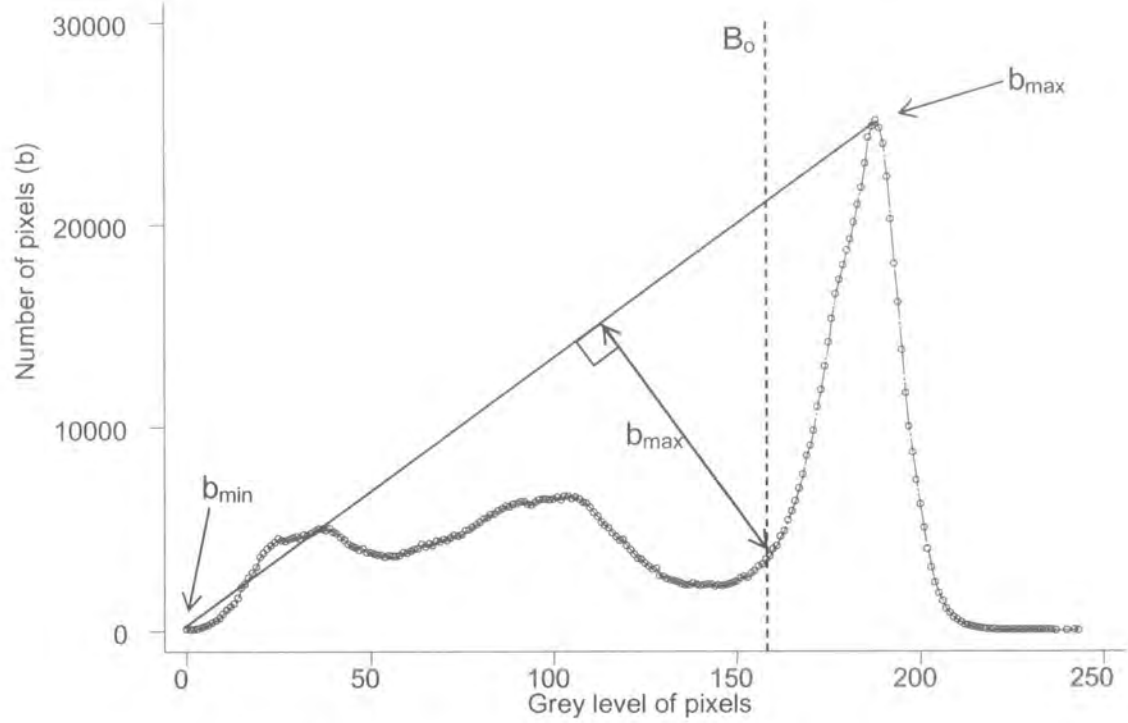


Figure 4.5 Triangular theorem image thresholding

Thresholding places a binary layer over the image. The binary is a grid layer at the resolution of the image that contains values = 1 if the value of the equivalent pixel is above the threshold value, and a value = 0 if the pixel value falls beneath the threshold. The binary overlay represents the aerial extent of the clasts (1 = clast). The distinct colour variation between the sediment and boulders made this stage of the analysis straight forward. The binary overlay gives a close representation of the presence or absence and shape of a clast. The series of filtering operations described above is found to return the highest precision between the initial image and the resulting binary overlay of all combinations attempted. The accuracy of the binary is visually assessed and found to consistently return a high correlation between the original image and the resulting binary layer. The filters are run in sequence via a macro embedded in PC_Image, automating the image processing procedure.

The third stage of the image analysis procedure is a series of morphological operations conducted on the binary overlay, commonly termed binary math (Figure 4.6).

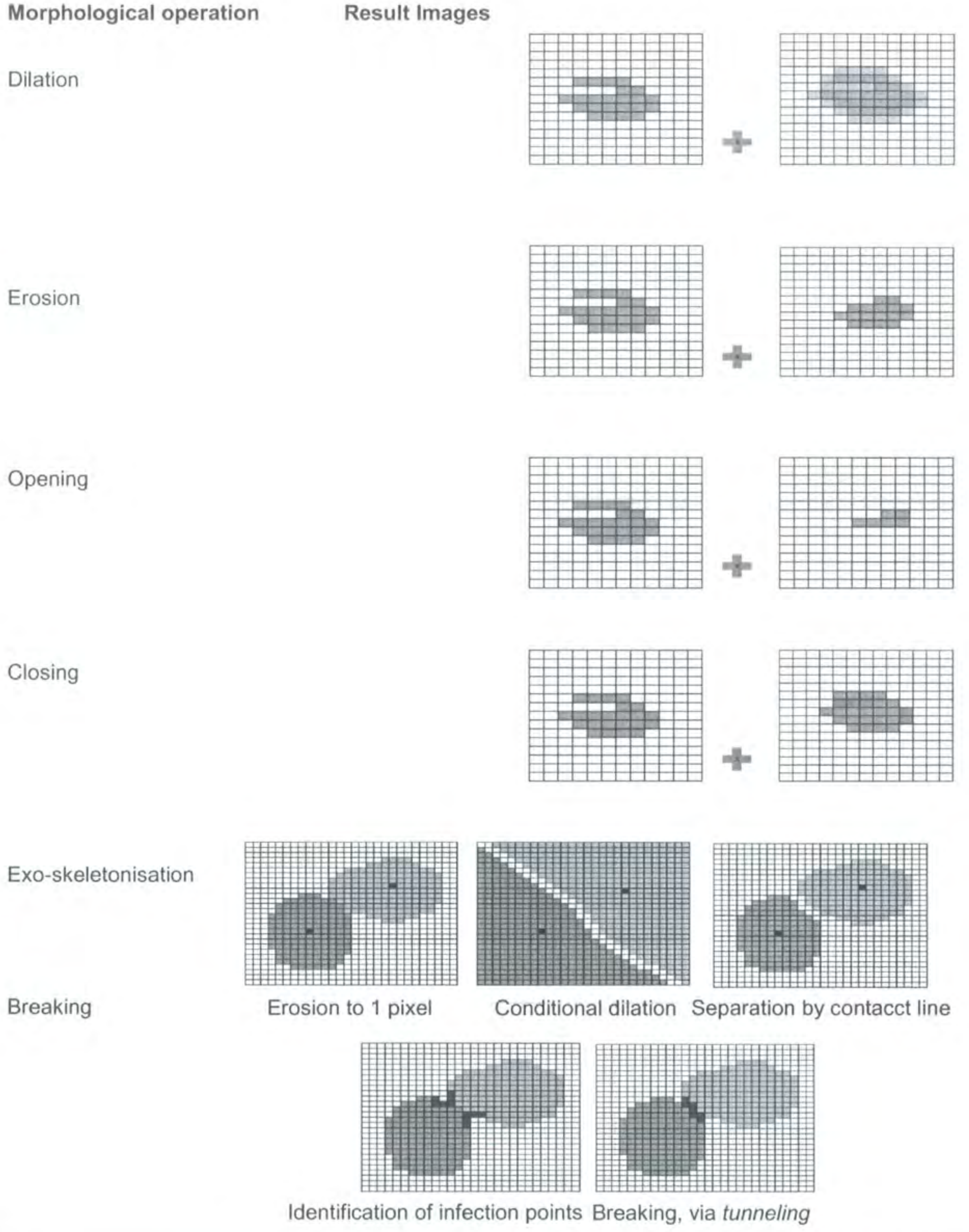


Figure 4.6 Binary math morphology

Binary math is intended to remove errors and noise in the binary overlay. The application of binary math is now described. First, a process whereby all single cell totally surrounded by cells with value = 1 are 'filled' as they are assumed to be erroneous points or holes. The close proximity of adjacent clasts on occasion results in agglomeration of neighboring clasts in the overlay, such that areas of sediments can be infilled as clast. These areas are manually reverted to sediment. The binary is then cleaned using a series of operations termed erosion and dilation (Figure 4.6). In combination these filters act to remove mono-pixel clasts and edge noise. Additionally an automated procedure to 'break' agglomerated clasts was developed. Breaking objects involves a process termed exoskeletonisation which dissects two clasts at inflection points on the clast perimeter (FFA, 2000). The dissection automatically slices the agglomeration at the inflection point, deleting a single line of clasts, until to two objects are separated. The results of the procedure are visually checked after completion. Ultimately a combination of methods is required to produce satisfactory results for each image. Final manual checks of each image are made to ensure the accuracy of the techniques deployed. Manual correction is required for around 0.5 % of clast contacts, undertaken using a digitizing tablet operating within PC_Image. The result of this operation is a binary layer considered to be a close approximation to the aerial extent of the clasts on the slope surface. Measurements of the individual clasts can be obtained from this layer.

4.3.3 Data analysis

Appropriate object measures were selected according to their relevance to slope process in the northeastern Badia (Table 4.1). Object measures are split into three broad categories. First, those which are specific to individual clasts, for example intermediate axis length. Second, those which apply to the whole image, for example percentage clast cover. Third, statistics which describe the spatial character of the *in situ* surface, for example clast orientations and clast centroid position. Spatial statistics are calculated in ArcGIS 8.1. Spatial analysis involved the creation Thiessen polygon nets and nearest neighbour statistics around a point pattern derived from the centroid of each clast. Additionally, the box fractal dimension for the binary layer was derived using Harfa 4.0, which provides a further description of the spatial character of the surfaces (Zmeskal *et al.*, 2001).

The mean number of clasts analysed in each image was 1157. A total of 26 individual object measures for each clast, in addition to 22 additional measures for the whole image and spatial statistics were derived. From the primary measures of clast form further secondary measures were calculated, for example total edge length for the whole image area, resulting in a total of over 70 variables for each plot position. The data were combined with measures of slope derived from the DGPS slope profile survey and dummy variables are introduced for geological variables. Additional variables included height, length and ken.par. The resulting data set of over 6 million numbers was analysed in Intercooled STATA 7.0. Prior to analysis the dataset was filtered. All clasts with an area less than 4 times that of one pixel or cell were dropped from the analysis. The form of clasts smaller than this size is dictated more by the resolution of the original image than the clast shape itself, so no meaningful statistics can be derived from these objects. The nature of the dataset allows data to be grouped as plot specific results, aggregated between plot positions over all sites, to individual profiles, or to individual slope forms. Additionally the data can be sorted by any variable, upon which filters can be applied.

Name	Measurement type	Morphological definition	Units
Image area		Total calibrated image area	m^2
Object number	Whole image	Number of clasts	#
Area percent		% of image covered by objects	%
Area		Area of each clast	m^2
Perimeter		Clast perimieter	m
Length		Major axis length	m
Breadth		Intermediate axis length orthogonal to major axis	m
Equivalent circle	Clast specific	Radius of circle with equal area as the object area	m
Minimum radius		Minimum distance from centroid to edge	m
Maximum radius		Maximum distance from centroid to object edge	m
Mean radius		Mean distance from centroid to object edge	m
Convex perimeter		Perimeter of the convex hull of the object	m
Centroid X		Centre of gravity of object in x plane	m
Centroid Y		Centre of gravity of object in y plane	m
Object / Hole		Object = 1, hole = 0	#
Mean Feret		Mean diameter of object seen from all angles	m
Max Feret		Maximum diameter of object seen from all angles	m
Min Feret	Spatial data	Minimum diameter seen from all angles	m
Feret (0)		Diameter if object seen from 0° orientation	m
Feret (45)		Diameter if object seen from 5° orientation	m
Feret (90)		Diameter if object seen from 90° orientation	m
Feret (135)		Diameter if object seen from 135° orientation	m
Orientation		Orientation of length relative to calibrated mage orientation	radians

Table 4.1 Image analysis derived clast measures

A series of calibration tests were undertaken to assess the precision of measurement of the image analysis technique and in addition the results were compared to those generated using the hand counting technique. The precision of measurement of the image analysis reduced with increased camera altitude as the pixel ground dimension increase. Shapes ranging in size from 0.02 m to 0.2 m in width were photographed at 2 m intervals between 2 and 28 m altitude. A standard measure of image analysis accuracy was used to compare dimensionless area and perimeter of objects of known dimensions, conventionally using object circularity (4 × area / perimeter^2) (FFA, 2000). Calibration objects measured were found to represent 90% of the actual object dimensions at heights of up to 28 m, for objects as small as 0.02 m intermediate axis. 99% accuracy in the ratio of measured to actual dimensions was found at a camera height of 12 m (Figure 4.7). Tests were also undertaken to assess the degree to which camera orientation influenced the measurements taken, but no effect was found.

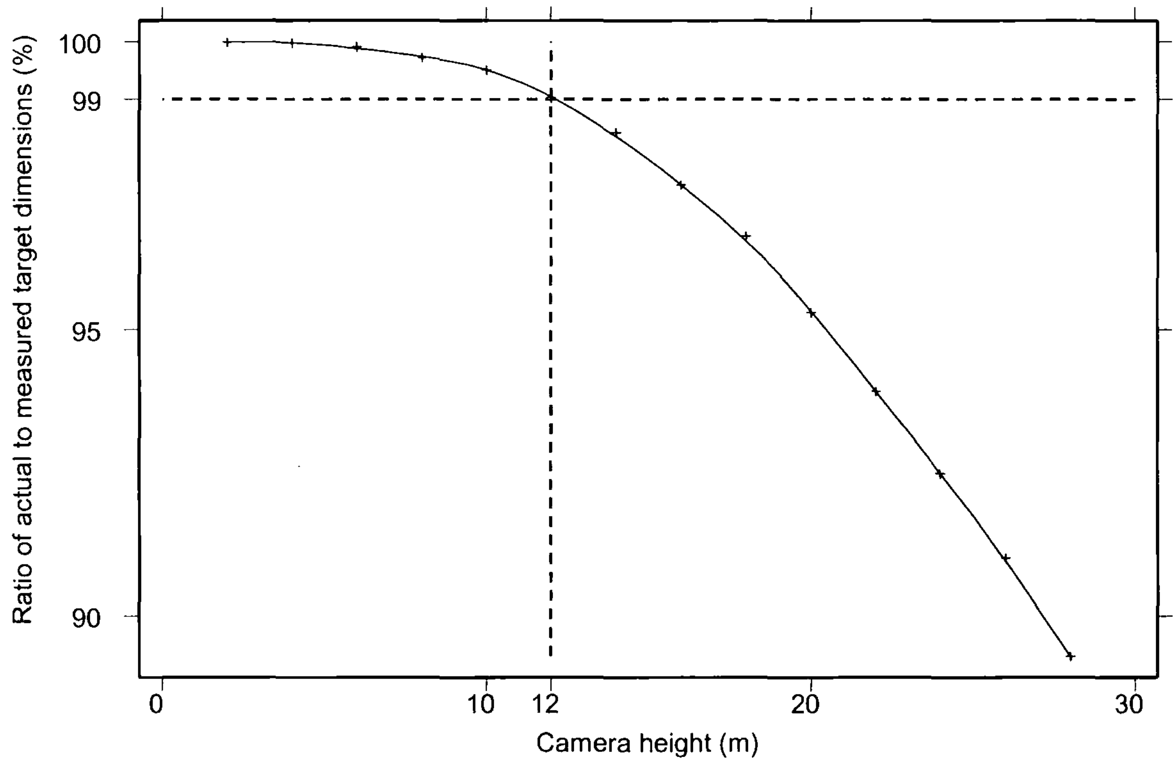


Figure 4.7 Measurement precision of the image analysis technique

4.4 Results

The results of the surface characterisation are presented in three sections. First, evidence of process modification of the clast and the surface configuration is discussed. Second, the influence of both slope form and geology is considered. Third, the spatial character of the clast surfaces is presented.

4.4.1 Features indicative of process action

4.4.1.1 Rounding and texture

Clast rounding and texture has been analyzed. A quantitative adaptation of Croft's (1974) matrix of planimetric particle shape and form has been developed. The matrix plots sphericity or elongation, as defined by the ratio of the intermediate to the major axis, against the roundness or smoothness as a measure of edge roughness. Additionally Macloed (*in press*) has developed a similar matrix of clast roundness and angularity, based on Eigenshape analysis. A quantitative adaptation of Croft's (1974) matrix can be applied to photographs of coarse clasts, based on the object measures derived by the image analysis procedure. The matrix describes clast elongation as the ratio of the intermediate (b) to major (a) axis, and crenulation or texture as the ratio of a perfect circle of equal intermediate axis to the actual area of the clast (Figure 4.7).

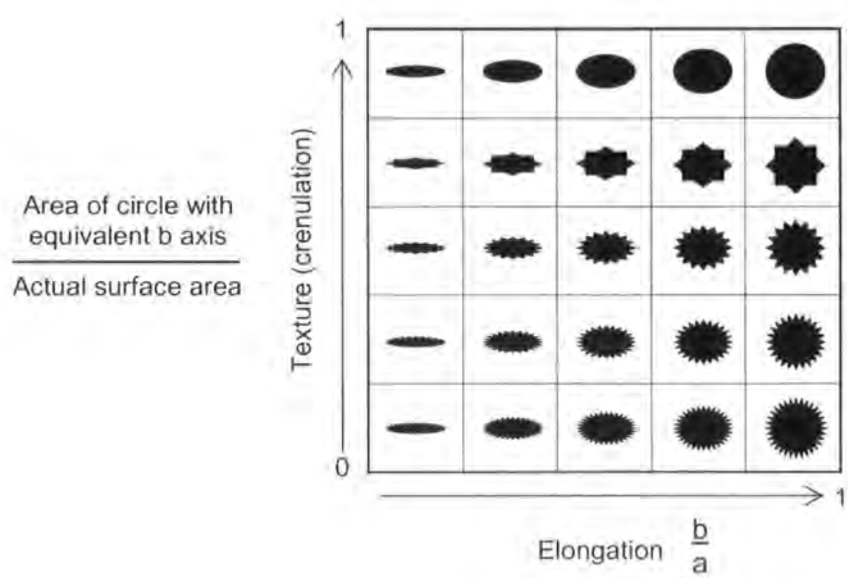


Figure 4.8 Adaptation of Crofts (1974) description of planimetric clast form

The adaptation of Crofts (1974) shape description to the planimetric measures derived from the image analysis shows a distinct variation down-slope in particle shape and texture (Figure 4.9). Clasts become progressively more round in planimetric form and less textured down-slope. The intensity of hydraulic process action at the slope bottom maybe enhanced due to greater volumes of overland flow and sediment load at this location. Levels of attrition and abrasion between clasts and sediments may account for smoother, more rounded clasts.

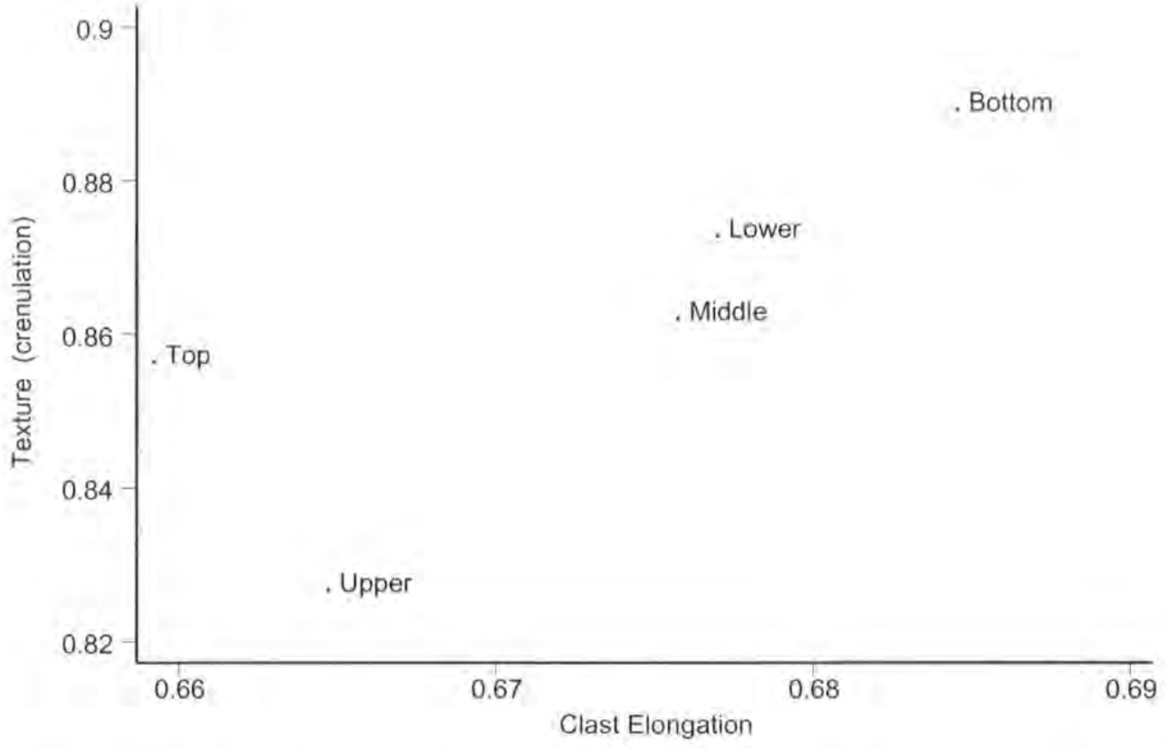


Figure 4.9 Variation of particle shape and texture with slope – all plots, grouped by plot position

The relative difference between plot locations suggests a complex relationship between clast shape and texture and location down-slope. The Top plot appears to return a slightly spurious degree of clast texture, implying that clasts are more textured than those at the neighbouring Upper plot. The Top plot is commonly located on or near to a bed rock outcrop. Particle smoothing is a function of the degree of physical and chemical weathering. The larger clasts at crest locations may be considered inert or immobile due to their size, limiting rolling due to high angularity, the lack of deformable underlying sediments, the low levels of overland flow due to absence of a significant up-slope area or the locking into the bedrock joint structure. The clasts still remain exposed to alteration by weathering, but may only move position much less frequently than at other slope positions. The exposed surfaces maybe heavily modified by weathering processes, but not by hydraulic action. In the field this suggestion is supported by high levels of desert varnish on clast surfaces at profile tops. Analysis of the larger clast sizes at the top of the slope profile commonly show a higher degree of rounding than for the smaller size fractions, supporting this suggestion. An example of this phenomenon is the preferential smoothing and rounding of larger clasts at CVT (convex profile, Top plot); clasts with intermediate axis > 0.15 m have a mean crenulation = 0.886 and mean elongation = 0.760, whereas clasts with intermediate axis < 0.15 m have a mean crenulation = 0.861 and mean elongation = 0.633. On the lower slope positions no such distinction by clast size in rounding or smoothing is found. Clasts here are potentially more mobile and susceptible to alteration by process action. Surface clasts are more uniform in shape and texture, irrespective of size. A logical assumption would be that this is a result of either increased action of slope processes, due to the increased up-slope area at these locations, or weathering due to increased levels of moisture down-slope.

The gradual increase in clast rounding and smoothing has several implications for understanding the nature of slope processes in action. The change in clast form suggests an increasing intensity of attrition or weathering processes down-slope, showing a link between ground surface character and plot position. Given the consistent variation in clast shape and rounding down-slope, it is suggested that the surfaces are not mature. No asymptotic degree of rounding or smoothing is apparent across the whole length of any of the profiles surveyed. The nature of the down-slope change can also be used to infer the type of processes acting to modify the surfaces. If a clast is picked randomly from the slope, the condition of the shape and texture of that clast could be confidently predicted from its location on the profile. Clasts in close proximity show a similar degree of modification or conditioning. If a catastrophic mechanism of surface modification and clast movement was a dominant control on surface form, less consistency in the variation in clast shape and rounding would be expected between each plot location. An alternative mechanism of clast movement is iterative surface modification. Under this condition all clasts at each location would experience a similar intensity of processes, as dictated by slope position.

4.4.1.2 Clast sorting and size

A typical clast size distribution derived from the image analysis shows a highly positively skewed distribution, the example displayed is from plot position STM (Figure 4.10), here displayed as a kernel density estimate. The minimum clast size enforced by the hand-counting can be seen to exclude a large and potentially significant proportion of the whole clast size distribution. A bimodal size population implies the action of a transport process. The finest mode may reflect a fine fraction of exogenous clasts whose size may allow them to be transported by concentrated overland flow (Poesen, 1987). The number of clasts in the larger fraction decreases geometrically with clast size, with only a few larger clasts present on the surface.

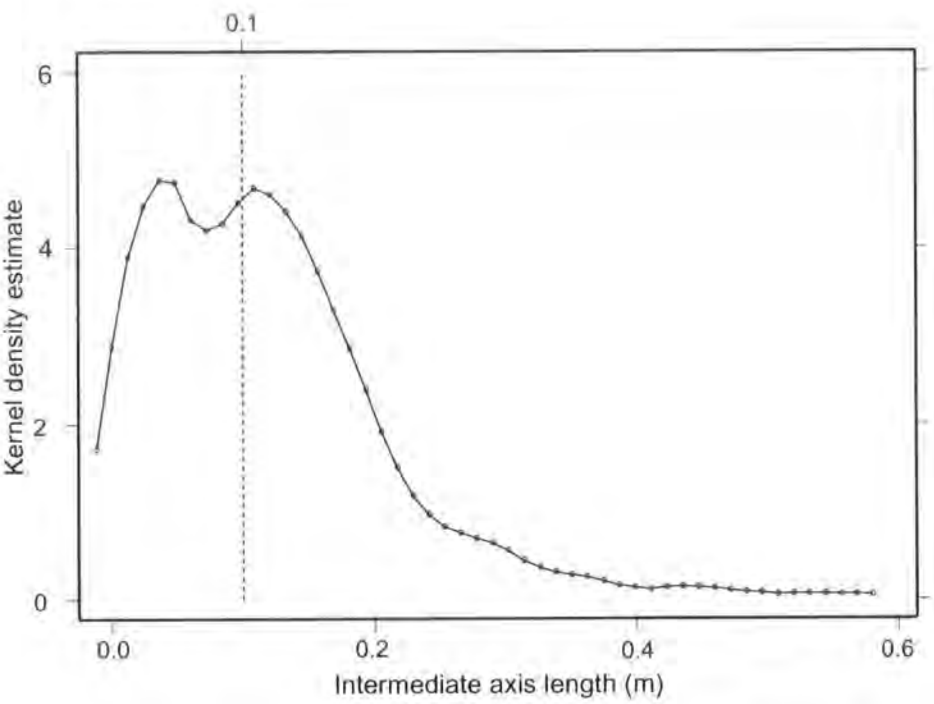


Figure 4.10 Kernel density estimate of intermediate axis length (STM)

The image analysis allows a more detailed insight into the nature of variation between slope positions, allowing a full clast size distribution to be presented. Normalized frequency distributions of the clast intermediate axis at the five slope positions show a marked variation in clast size distribution down-slope (Figure 4.11).

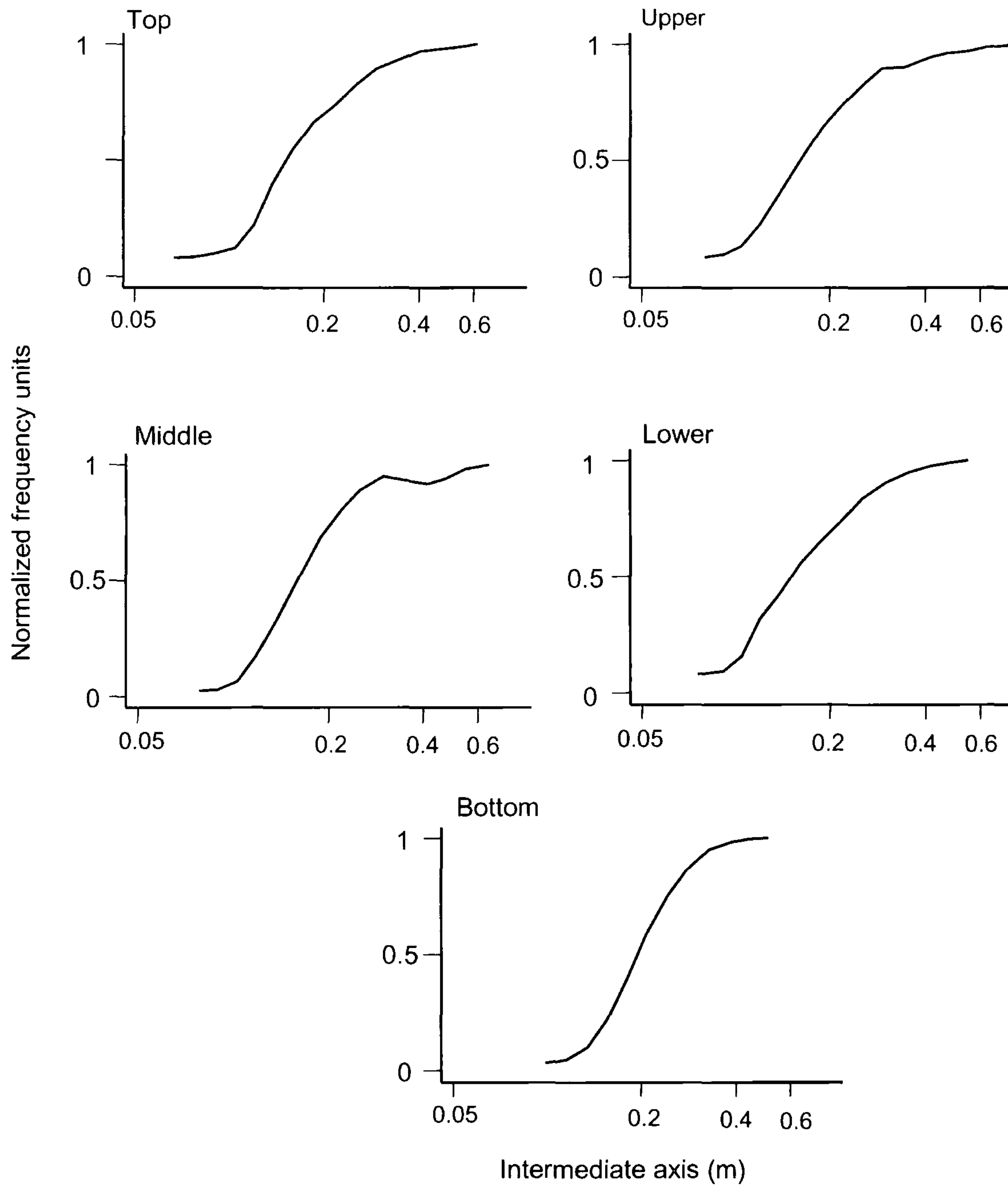
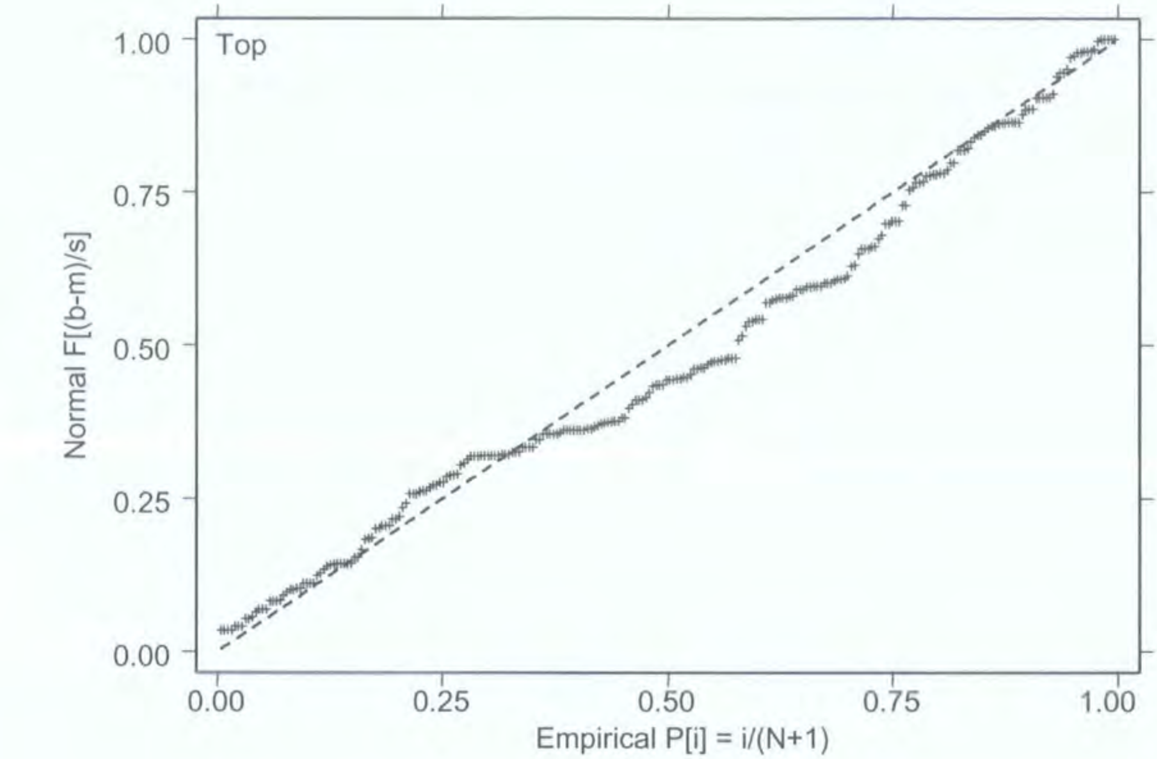


Figure 4.11 Normalized frequency distributions of intermediate axis lengths for all plots, grouped by plot position

An increasingly constricted clast population distribution towards the bottom of the slope is identified. Bottom plot locations exhibit a smaller proportion of the population in the finest clast size fraction with intermediate axis less than 0.1 m. Equally, the proportion of clasts in the largest size fraction (> 0.4 m) seen at the higher plots reduces down-slope. The preferential sorting and removal of finer clasts at the lower slope locations (Lower and Bottom) is clear. At the Lower and Bottom locations transport capacity of overland flow would be higher due to increased up-slope area, and concentrated overland flow may act to remove the finer clast fraction (Poesen, 1994). Additionally, there is a reduced influence of bedrock on clast size in the down-slope portions of the profile.

The clast distribution alters from a leptokurtic to a platykurtic distribution from Top to Bottom of the slope profile. The proportion of clasts in the finest fraction reduces notably between the Top and Upper plots, but the proportion in the larger clast fraction appears more persistent down the profile. If clasts are large they tend to remain large, implying that the modification of the surfaces is again limited, potentially as a result of the resilience of the basalt to weathering.

Further analysis of clast distribution identifies an increased level of normality in population distribution down-slope, suggesting that the action of slope process acts to focus the clast population distribution around a mean value. Normalized probability plots of intermediate axis length for the Top and Bottom plot positions demonstrate the change in the style of the clast size distribution down-slope (Figure 4.12). The distribution of clasts becomes less irregular towards the bottom of the slope profile, with both fine and coarse fractions becoming tightly constricted to a normal distribution, indicated by the dashed line.



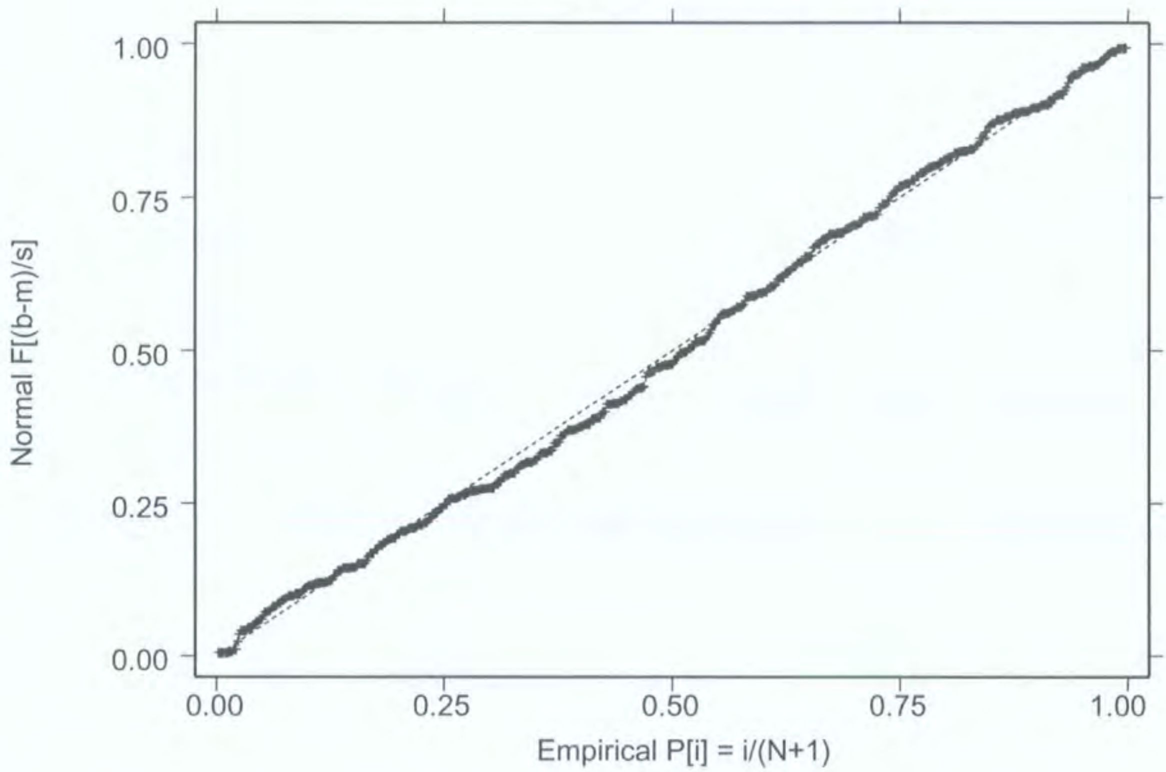


Figure 4.12 Example of normalized probability distribution of intermediate axis length (profile ST)

A further indicator of slope process is the nature of the size distribution of clasts between slope positions. The coefficient of variation (Equation 4.1) is employed as a relative indicator of clast population dispersion down-slope. This analysis is performed on the intermediate axis, as a less spurious measure of clast size. A lower value of Cv_b indicates a more tightly constricted distribution of clast sizes, suggesting a greater degree of sorting (Figure 4.13).

(Eq. 4.1)

$$Cv_b = \frac{\sigma}{\left(\frac{\sum b}{n}\right)} \times 100$$

where: Cv_b = coefficient of variation

σ = standard deviation of intermediate axis length

b = intermediate axis length

n = number of clasts

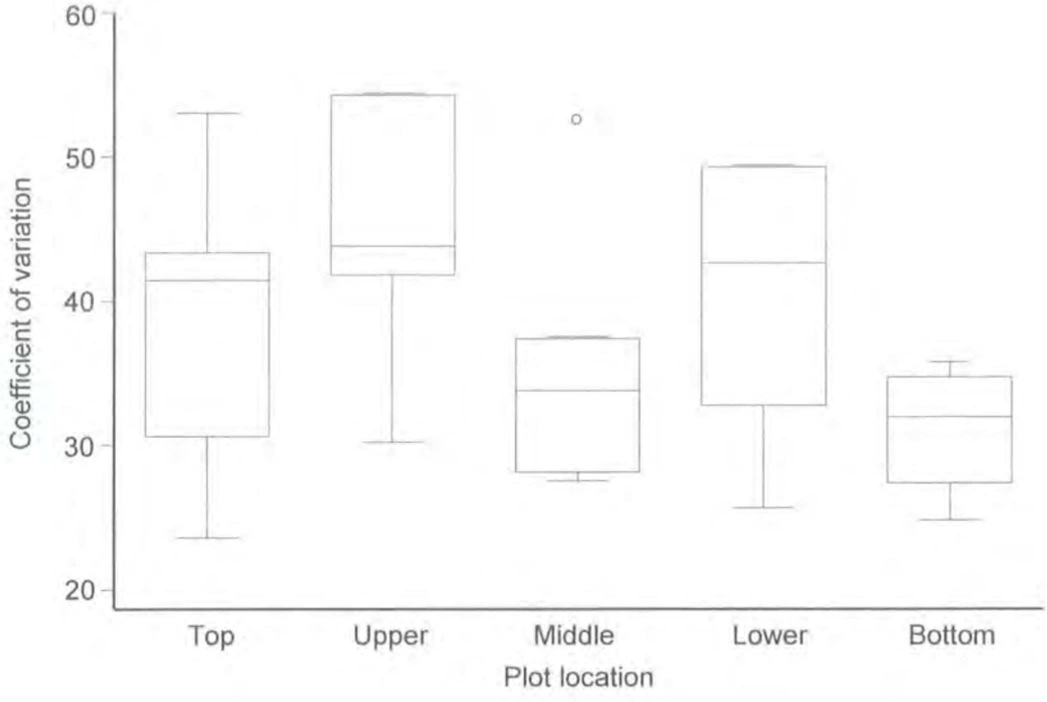


Figure 4.13 Box plot of the coefficient of variation for all 29 plots, by plot position down-slope (the box represents the interquartile range, intersected by the median, the whiskers show the upper and lower adjacent values, and observed points outside the adjacent values are indicated by dots

The analysis of the coefficient of variation suggests a more complex down-slope change in surface form that described so far. Median values of Cv_b appear to reduce towards the toe of the slope but the nature of variation does not follow the gradual change as seen previously. Attempts to relate this variation directly to mean slope angle, mean distance down-slope or other averaged slope variables only yields weak correlations. No association is found with the loci of maximum slope angle. Top, Middle and Bottom plots follow a trend of increasing clast sorting and a tendency for the variation of Cv_b to focus around the median towards to bottom on the slope. The Upper and Lower plots, return a lower degree of clast sorting, as represented by a higher value of Cv_b. No single slope variable can explain the nature of this variation.

The implication is that the nature of the clast population is controlled by multiple interdependent factors. Additionally, given the inherent complexity of the surfaces is it perhaps unreasonable to expect a linear change in all characteristics of the surface or clast form with slope. Furthermore, the averaging of results generated from the 7 sites masks the already established diversity between the various slope forms and geologies. Clasts are modified to a more uniform intermediate axis length, mirrored to a certain degree by a reduced value of Cv_b.

4.4.1.3 Ground cover

Percentage ground surface cover varies systematically with slope position in the northeastern Badia (Allison *et al.*, 2000). The previous method was an indirect approximation of percentage ground cover derived from an estimation of the exposed clast surface area derived from an elliptical function placed around the major and intermediate axis. Conversely the image analysis examines the actual ground cover, at pixel ground resolution of greater than 0.01 m, over a much large sample area.

Aggregated statistics of all 19 plots on the Abed basalt suggest that a maximum clast cover percentage is found at the Upper plot position (Table 4.2). Analysis of variance (ANOVA) indicates a significant difference in ground cover between the slope locations, where $F = 42.49$ far exceeds the critical value of 2.741 for degrees of freedom 4 to 28. Results of ANOVA undertaken on axis dimensions should be viewed with caution. ANOVA assumes a normal distribution in variables. Axis dimensions are commonly highly skewed, so the significance in difference may be an artifact of the varying clast size distribution down-slope. The results largely agree with those derived by Higgitt and Allison (1998) for Abed basalts (Table 4.2). The absolute differences between plot positions appear more subtle when derived from the data collected from the image analysis. The only notable difference between locations is at the Bottom plot position, which from the image analysis shows a 4% increase in ground surface cover from the Lower plot position. Conversely Higgitt and Allison (1998) report a significant fall in ground surface cover between the same two plot positions. Additionally, the hand-counting technique undertaken by Allison and Higgitt (1998) returns mean percentage ground cover 3.3 % higher than the image analysis technique.

Slope position	**Mean ground cover (%) (σ in brackets)** **(Image analysis)**		**Mean ground cover (%) after: Higgitt and Allison (1998)**
Top	39.074 (7.334)		42.88 (17.08)
Upper	42.536 (6.703)		48.11 (14.94)
Middle	34.817 (8.577)		40.98 (16.02)
Lower	25.815 (10.090)		38.65 (18.42)
Bottom	29.555 (9.044)		16.96 (9.00)
Mean	33.806 (10.159)		37.516 (12.092)
ANOVA	df	F	Probability
Ground cover	28	42.49	0.000

Table 4.2 Variation of ground surface cover with plot position

To investigate this discrepancy and ascertain whether this is a function of method or location, the hand-counting procedure was undertaken on the image analysis plots at all 19 sites on the Abed basalt at Marab Swayed. The location of the hand-counting technique was positioned using the procedure of Allison and Higgitt (1998). A surprising diversity in results emerges from the different techniques of surface characterisation employed (Figure 4.14). The result suggests that the hand-counting has a tendency to overestimate percentage ground cover by up to 15%. The discrepancy previously seen at Bottom plot positions appears to be a function of profile location rather than technique, as the hand-counting at the image analysis plots produces a similar variation between plots as the image analysis. The ellipse approximation to calculate ground surface cover generated from the image analysis derived intermediate axis shows a similar result to that presented by Allison and Higgitt (1998).

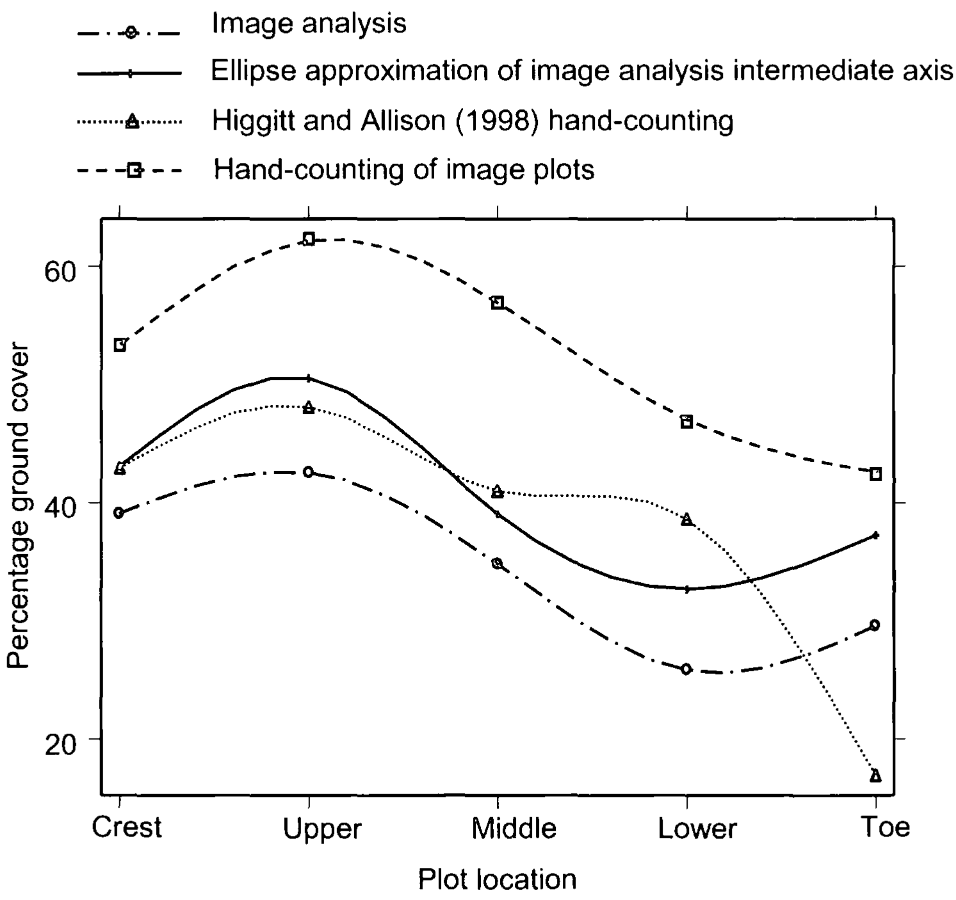


Figure 4.14 Down-slope variation in ground surface cover as calculated from image analysis and hand-counting techniques (points are connected with a cubic spline to emphasize the nature of down-slope change between methods)

The discrepancy observed can be attributed to both the sample site position and the method of measurement. Despite the hand-counting eliminating the finer clast fraction percentage ground cover appears consistently higher when derived using this method. This is attributed to two primary causes. First, the ellipsoid approximation assumes an idealized clast shape, with a perfect ellipsoid form. It is clear from an examination of the images of the surface that clasts are commonly faceted and angular and therefore in a planimetric projection the majority of clasts have a lower surface area than an ellipse of equivalent major and minor axis lengths. Secondly, the ellipse approximation assumes clasts are positioned such that both the major and minor axes are exposed above the sediment surface. The surface area of clasts which are submerged such that the major and intermediate axes are not exposed will return an exaggerated surface area, leading to an increase in the ground surface cover of the plot. The variation in ground surface cover between plot locations is consistent with a modification of the surface character by slope processes. The decrease in percentage ground cover runs in parallel with the alteration of the clast size distribution, shape and texture variation. Increased attrition between clasts, the preferential removal of fine clasts and enhanced weathering due to highly moisture levels may account for this.

In addition to absolute values of surface character, the degree of variation in surface cover at a given plot position varies systematically with slope. In the example of ground surface cover, values returned at Bottom plot positions are highly variable between profiles. The decrease in the degree of variation downslope is reflected by a strong relationship between the percentage ground cover and the standard deviation of percentage ground surface cover (Figure 4.15).

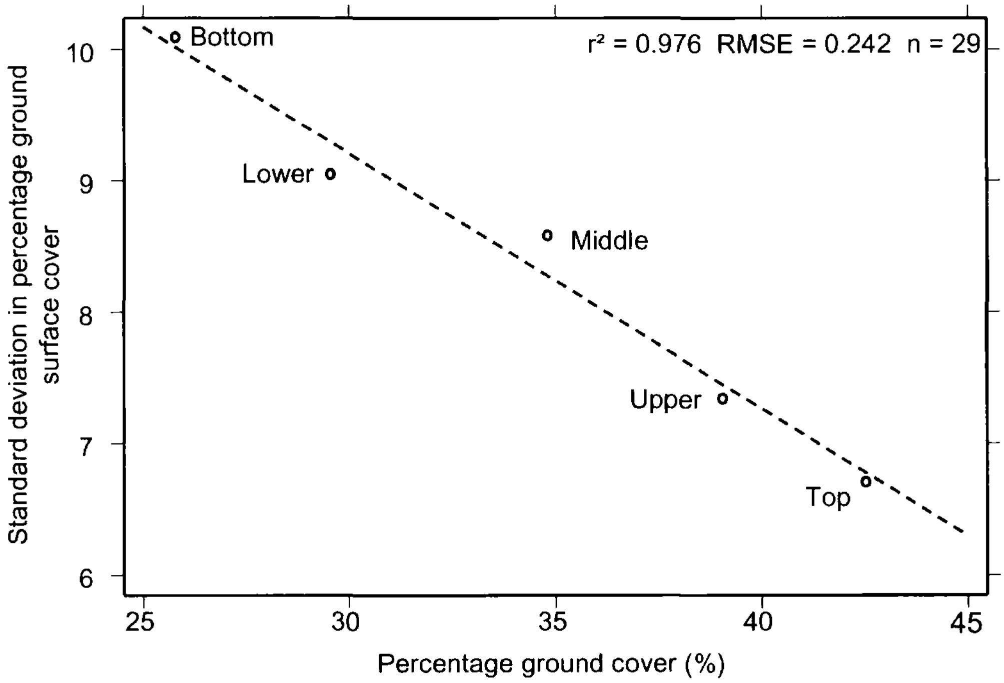


Figure 4.15 Relationship between percentage ground surface cover and the standard deviation of ground surface cover at five plot positions down-slope

Bottom plot positions, as those with the lowest percentage ground surface cover, exhibit the highest standard deviation of ground surface cover. If percentage ground surface cover is a function of surface modification as is suggested, the increase in standard deviation in percentage ground surface cover down-slope suggests that slope processes are not convergent. Slope processes act to create diversity in surface character rather than tending to converge to one type of surface configuration. Again this implies the complexity of the surfaces, with multiple interdependent factors acting to create a non-linear response of the surfaces to slope process. Additionally a homeostatic relationship between form and process in suggested. Surface character is modified by process, but equally process is modified by form.

There is abundant field evidence to suggest that Bottom plot positions undergo a greater diversity of formative processes. Water marks are frequently apparent on clast perimeters at profile toes, suggesting inundation by standing water either in the over bank in the wadi channel or as water standing in Qa'a or Marab. Dust devils scour the surfaces of the Qa'a and Marab resulting in the entrainment of a large amount of material, both via saltation and entrainment. The smooth playa surfaces of the Marab or Qa'a present little aerodynamic roughness (0.00013 – 0.00015 m, Lancaster *et al.*, 1991). Conversely the boulder mantled slopes present considerable roughness (0.1480 – 0.02860 m, Lancaster *et al.*, 1991). The roughness of the clastic surfaces is of particular importance in disrupting the critical zone of aeolian transport, in the saltation layer (Nickling, 1987). The result of this is massive deposition at the Bottom plot position on the slope at the boundary of Qa'a and Marab features (Plate 4.5). Deposition has been observed to be further enhanced by the topography channelling of local winds by the incised wadi networks. It is suggested that in addition to being influenced by slope process and run-off, surface character a toe locations is further complicated by a greater intensity of other processes than is experienced at the up-slope locations.

Aeolian deposition the day after a large dust storm event. Three photographs taken from (A) 2 m, (B) 10 m and (C) 25 m from the edge of Marab Swayed, showing a marked decrease in aeolian sediments with distance from the pan surface

Plate 4.4 The variation of aeolian sediment deposition with increasing distance from the perimeter of Marab Swayed

Further detailed descriptors of surface character emphasise the nature of change suggested above. Table 4.3 illustrates a range of clast and plot variables aggregated between slope locations. Although general down-slope variations in clast surface appear to be coherent with the variables previously presented, Table 4.3 highlights the complex variation in clast surface character between slope locations. The resulting suggestion is that the value of aggregated, or average statistics between sites, is somewhat limited. The degree of variation indicated by the high standard deviation values illustrates the between sites variability. Systematic differences due to location may mask within site variability. To proceed further therefore the data should be reanalysed by individual slopes and sites and basalt types, allowing linkages between slope form and surface cover to be explored further.

Plot location (sample size)			Clasts per m^2	Total edge length per m	Mean clast area (m^2)	Mean clast perimeter (m)	Mean circularity	Major axis (m)
Top	(4521)	Mean	26.67	8.54	0.023	0.48	0.76	0.17
		s.d.	9.74	1.27	0.027	0.41	0.26	0.12
Upper	(2644)	Mean	36.93	11.43	0.016	0.50	0.73	0.16
		s.d.	16.72	2.89	0.027	0.57	0.34	0.14
Middle	(4919)	Mean	23.89	8.83	0.018	0.49	0.77	0.17
		s.d.	11.36	3.28	0.025	0.45	0.28	0.13
Lower	(3379)	Mean	30.43	8.16	0.013	0.42	0.79	0.15
		s.d.	12.19	2.52	0.022	0.43	0.29	0.12
Toe	(5852)	Mean	22.28	8.63	0.016	0.45	0.80	0.17
		s.d.	6.99	2.49	0.016	0.27	0.21	0.09

Table 4.3 Variation in ground surface character with slope position

4.4.1.4 Appropriate statistics

Analysis and correlation of single descriptors of slope and surface character have yielded poor correlations, raising two issues. First, are the measures adopted appropriate to the question being asked? Second, are the surface more complex, whereby the influence of each control on surface form varies and is varied by the influence of other factors? A series of weighted clast specific measures has been devised, under the recommendations of Dunkerley (1996) (Table 4.4).

Statistic	**Formula**
Perimeter weighted mean diameter (EdgewMb)	$x = \dfrac{\sum_{i=1}^{n} d_i^2}{\sum_{i=1}^{n} d_i}$
Area weighted mean diameter (AreawMb)	$x = \dfrac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2}$
Volume weighted mean diameter (VolwMb)	$x = \dfrac{\sum_{i=1}^{n} d_i^4}{\sum_{i=1}^{n} d_i^3}$

Table 4.4 Table of appropriate surface characteristics developed (after Dunkerley, 1996)

Correlations undertaken with these appropriate statistics yield higher levels of significance, strongly supporting Dunkerley's (1996) suggestion of adequacy (Table 4.5).

Statistic	Slope length (m)	Slope height (m)	Plot angle (°)	Whole slope angle (°)	ken.par	Down-slope plot distance (m)
VolwMb	**0.548**	*0.399*	0.052	0.358	0.158	0.03
AreawMb	**0.526**	*0.377*	0.05	0.349	0.153	0.05
EdgewMb	**0.482**	0.341	0.037	0.327	0.135	0.088
b	0.129	0.095	0.002	0.082	0.027	0.04

Table 4.5 Correlation coefficient of appropriate statistics and slope variables (significant correlations ($\alpha = 0.01$ are indicated in bold, $\alpha = 0.05$, indicated in italics)

The transformation of the intermediate axis dimensions results in a higher level of correlation between the surface character variable and the slope variables, than with any of the other direct measures of surface form. VolwMb consistently generates the highest levels of correlation, followed by AreawMb and lastly EdgewMb. Despite that fact that the statistics return a greater significance using the data provided by the image analysis questions are raised about their use. AreawMb and EdgewMb respectively attempt to gain an approximation of a facet of clast form that is deemed more significant in controlling slope hydrology. Actual measures of clast area, approximated by AreawMb, and clast perimeter, approximated by EdgewMb, have been generated by the image analysis, but correlation of the actual values with slope variables yields low levels of significance. Variables are now considered in a multivariate analysis of the relationship between slope form and surface character.

4.4.1.5 Multivariate analysis

In an attempt to relate surface character to slope form, multiple regression models have applied to a selection of surface cover variables and slope variables. The suitability of the variables available for multiple regression is somewhat questionable. Multiple regression assumes normality of homogenous residuals. The range of slope data is highly restricted, due to the low undulating topography. Only a few plot positions show any significant departure from the mean low plot angle (3.3°). Chi squared tests undertaken on a range of transformations suggest no significant gains are to be made through data transformation.

The bimodal distribution of slope profile shape, and the limited sample number (9 sites) is restrictive, but the semi-quantitative method of sample sites selection acts to increase the value of the statistics. The regression has been undertaken with both site specific slope variables, for example plot angle and up-slope distance and area, in addition to whole slope variables, for example slope length, slope height, ken.par, whole slope angle. Independently, the two groups of variables yield poor results. When combined more success is gained. Regression models constructed between three measures of surface character, whole slope and plot variables yield significant correlations (Table 4.6).

	Percentage cover			Mean crenulation			Mean elongation		
	r^2= **0.652**	Prob > F = 0.00		r^2= **0.647**	Prob > F = 0.000		r^2= **0.652**	Prob > F = 0.00	
Variable	Coefficient	Standard Error	ß	Coefficient	Standard Error	ß	Coefficient	Standard Error	ß
Slope length	0.102	0.00	1.500	-0.000	2.30e-06	-1.573	-0.000	1.79e-06	-1.587
Slope height	0.641	0.014	0.413	-0.004	0.000	-0.565	-0.002	0.000	-0.367
Plot angle	0.167	0.013	0.065	-0.001	0.000	-0.051	-0.001	0.000	-0.148
Slope angle	0.801	1.000	0.451	-0.000	0.000	-0.055	-0.003	0.000	-0.446
ken.par	64.405	0.000	0.499	-0.319	0.004	-0.611	-0.215	0.003	-0.525
Plot distance down-slope	-0.056	0.000	-0.684	0.000	1.80e-06	0.538	0.000	1.41e-06	0.456
Constant	-26.861	0.6716	.	1.145	0.003	.	0.883	0.002	.

Table 4.6 Multiple regression diagnostics between slope and ground cover variables ($P < 0.0001$ for all regression models) ($\alpha = 0.01$, $r^2 = 0.487$)

Significant correlations are found between slope and plot variables and percentage cover (r^2 = 0.652), mean crenulation (r^2 = 0.647) and mean elongation (r^2 = 0.652). The suggestion is that slope surface cover and clast shape can be directly linked to slope form and plot slope character. The poor results of regression between solely slope and solely plot angle measures suggests that cover percentage is not independently linked with slope form, nor plot angle. Surface cover can only be understood if slope parameters and plot statistics are considered within a multivariate regression model.

The normalised beta coefficients (ß) indicate the relative strength of each of the predictor variables within the regression model. Beta coefficients are measured in standard deviations and are hence directly comparable between variables. Analysis of beta coefficients suggests the dominant variables in the regression model. Notably slope length and height consistently return the high ß values. In the regression of percentage cover a standard deviation increase in slope length would result in a 1.5 standard deviation increase in predicted ground percentage cover, with the other values in the model held constant. Slope dimensions are critical controls on ground surface cover within this model.

Additionally, ken.par appears to be influential. In the prediction of mean crenulation a standard deviation increase in ken.par results in a 0.611 standard deviation decrease in mean clast crenulation and correspondingly a 0.525 decrease in clast elongation. Increasingly convex slopes tend to promote higher levels of clast edge smoothing. Again it is dangerous to generalize from aggregated statistics. For example, ken.par values will not report down-slope change as they are effectively aggregated across the whole slope. A single ken.par value represents a range of slope angles down the slope profile, rather than a local plot parameter that influences plot specific surface characteristics. Logically, three slope crest locations with equal slope characteristics, for example plot angles and distance down-slope, but diverse ken.par values would not be expected to be significantly different. Therefore, regression of measures of whole slope form to predict local surface character, which has already been shown to vary dramatically, appears paradoxical. To further this analysis it is suggested that individual sites are considered in the context of their specific slope form, angles and ground cover features. By examining the relationship between slope and surface at this scale it is hoped that further linkages between process and form can be identified.

Variations in clast shape, texture, size and sorting are all coherent with a model of progressively increasing process action down-slope, supporting the suggestion that the surface character is dictated by slope controlled hydrological processes. Spurious variation in Top and Bottom plot positions can be accounted for by either the presence and influence of bedrock and the additional influence of other formative processes respectively.

The nature of variation between the Top and Bottom plots locations is consistent with hypothesis of surface modification by slope hydrology but the nature of variability is complex. It is evident that the variation in surface character is complex. No single slope or ground cover variable is able to generate a statistically significant explanation or clast surface form at all plots surveyed. Either a high degree of local control, which is masked in the aggregated statistics presented above, or alternatively the surfaces appear to exhibit a non-linear nature of variation is surface character. Controls on surface form appear to have a variable influence dependant on location.

4.4.2 Influence of geology and slope on ground surface character

Within this study, the range of slope forms within one basalt type at Marab Swayed allows the influence of slope and basalt to be examined. The influence of underlying geology is manifested by a distinct difference between basalts, despite the variation of slope forms (Table 4.7).

	Image analysis (sample number)		**Hand count at image plots** (sample number)		**Hand count** (after Higgitt and Allison, 1998a)	
Basalt type	Mean intermediate axis (m)	σ	Mean intermediate axis (m)	σ	Mean intermediate axis (m)	σ
Abed	0.123 (14354)	0.087	0.1596 (1347)	0.576	0.1624	0.143
Bishriyya	0.0915 (3961)	0.073	0.1386 (506)	0.585	0.1198	0.117
Madhala	0.1025 (3759)	0.098	0.1447 (488)	0.602	0.1298	0.254

Table 4.7 Variation in intermediate axis length for Abed, Bishriyya and Madhala basalts by three characterization techniques

Mean intermediate axis generated by the image analysis is consistently lower than that derived by the hand counting both on the image analysis plots and from the data previously compiled by Higgitt and Allison (1998). To reiterate: the image analysis measures the exposed axis; those dimensions of the clast portion which is exposed above the sediment surface. Additionally, variation in results maybe attributed to the adequacy of the sample size and the accuracy of measurement. Maximum clast sizes surveyed by the two techniques reflect this. For example, on Abed basalts the mean intermediate axis of the four largest clasts surveyed using hand counting was 0.423 m, whereas from the image analysis this value is 0.752 m. The difference in results between techniques suggests both the importance of sample area returning a representative bulk sample, in addition to the role of any operator bias in plot selection.

Individual clast form also varies between basalts (Figure 4.16), which may be indicative of either an increased exposure to modification of the clasts by weathering, or secondly, a reflection of the resilience of the basalt mineralogy to weathering. The Bishriyya, as the youngest flow (0.1 to 1.45 million years) has the most tightly constricted distribution of clast shape and texture, whereas the oldest Abed (8.9 million years) and the Madhala (1.96 to 3.41 million years) show an increased dispersion of clast shapes and textures (Figure 4.16). A direct link between clast form and basalt age is not consistent. It would perhaps be unreasonable to assume that present surface clasts have been remained at the surface for a period comparable to the age of the underlying basalt, and environment that the clasts have experienced has been consistent. The variation in clast shape is therefore more likely to be a result of basalt mineralogy and locally controlled modification by weathering of the clasts.

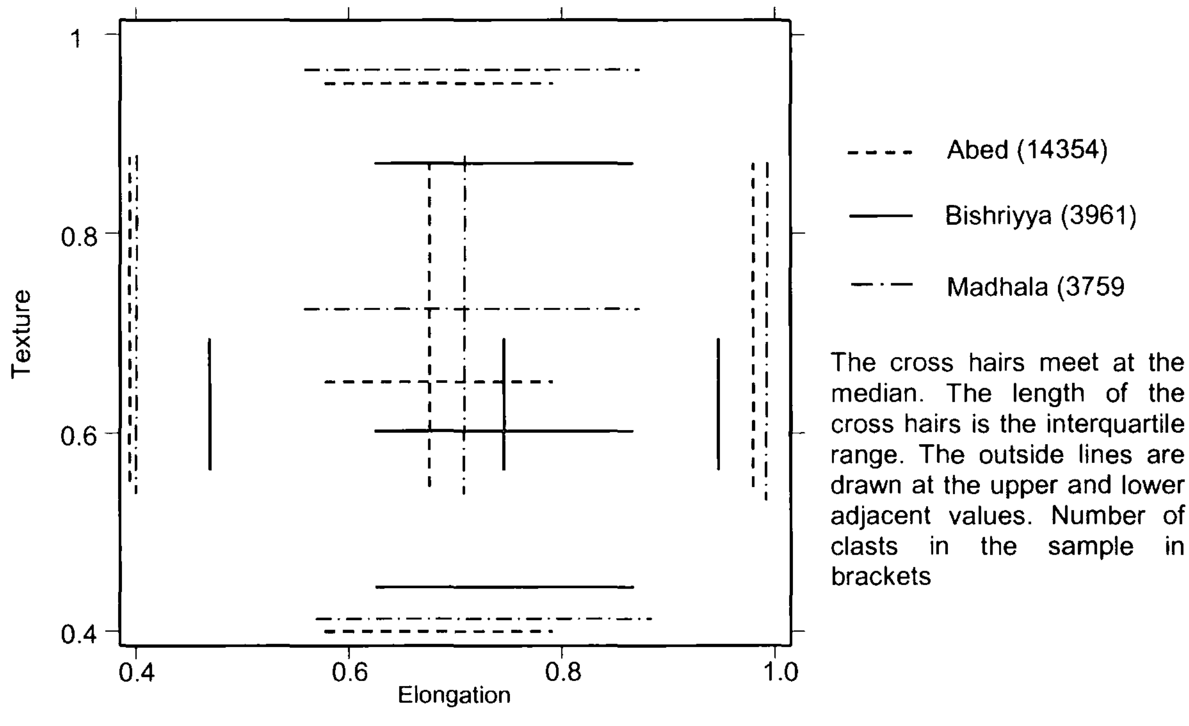


Figure 4.16 Variation in clast shape and texture between basalt types

A comparison of clast size distributions, specifically skewness and Cv_b, for individual basalt types indicates a clear distinction in surface form between basalts (Table 4.8). Results appear contradictory. Absolute values of Cv_b are highest on the Abed when generated using the image analysis, whereas the hand-counting contrary shows the clast dispersion on the Bishriyya to be greatest. The coefficient of variation is strongly dictated by the presence of the finer fraction in the clast population, which the hand counting eliminates. Skewness is influenced in a similar manner, whereby the large number of smaller clasts dominates the nature of the tail of the distribution in the finer clast fraction.

Analysis of variance shows that the difference between basalts in both Cv_b and the skewness of the distribution identified by the image analysis is significant.

	Cv_b (standard deviation)		Skewness	
Basalt	Image analysis	Higgitt and Allison (1998)	Image analysis	Higgitt and Allison (1998)
Abed	37.332 (8.134)	34.83 (5.88)	1.379 (0.869)	0.71 (0.80)
Madhala	35.556 (9.651)	36.83 (6.61)	1.557 (0.734)	1.07 (0.62)
Bishriyya	33.331 (9.176)	37.81 (10.99)	1.892 (0.729)	1.41 (0.5)

Table 4.8 Clast sorting by basalt type

A tentative temporal link between basalt age and clast population sorting is shown, which appears to be opposite to the trend identified by Higgitt and Allison (1998). The clast size population becomes progressively more dispersed, but less skewed with age, suggesting that the surface character diverges to a less sorted and loosely constricted size distribution. The change in the nature of the clast population demonstrates a temporal modification of the surfaces, with the oldest surfaces supporting fewer finer clasts. The ergodic treatment of the individual basalt flows assumes that all surfaces on all basalt types follow the same evolutionary trajectory and each began with the same type of ground surface cover from emplacement and that the nature of surface modification experienced by all basalt has been similar. Given that the largest mean size of clasts appears on the oldest Abed flows (Table 4.8), the suggestion of a gradual alteration of surface clasts with time is incongruous; clasts cannot increase in size through time. The trend may be a reflection of the more extensive weathering of larger clasts through time, which then persist at the surface.

Evidence of slope processes indicates a temporal modification of the surface clasts through enhanced clast smoothing and rounding with age. The sorting of the clast population does not support the trend suggested by clast texture, showing a decrease in clast population sorting with age. Additionally, the highest ground surface cover is found on the older Abed flows (Table 4.9). Again the relative variability between sites is consistent between characterization techniques, but the absolute values generated are diverse.

Basalt	Percentage ground cover (%) (σ) (image analysis)	P{percentage ground cover (%) (after Higgitt and Allison, 1998) (σ)	Percentage ground cover (%) from ellipsoid approximation from hand counting of image plots (σ)	% ground cover of ellipsoid approximation of apparent axis (σ)
Abed	38.179 (7.524)	50.77 (14.27)	57.882 (14.871)	44.296 (8.954)
Madhala	27.414 (8.446)	49.61 (15.30)	42.518 (17.012)	38.741 (9.756)
Bishriyya	24.788 (8.861)	46.44 (21.71)	37.139 (19.804)	30.617 (11.251)

Table 4.9 Percentage ground surface cover between basalts, by different surface characterization techniques

Results from all methods of characterization show a consistent nature of variability between the three basalts. The Bishriyya basalt shows the lowest percentage cover, but a higher standard deviation. Absolute differences between basalts do overlap between techniques, reflecting the subtle nature of variability on the surfaces and the resulting necessity for a precise characterization technique. The results generated do not adhere to a model of surface modification via attrition and weathering of clasts by hydrological processes through time. Percentage ground surface cover increases in parallel with basalt age, implying that older, presumably more mature slopes, are dominated by larger clasts. No explanation for this phenomenon as a result of surface hydrology or process modification appears to be available. The nature of variation is either as a result of mineralogical variability dictating the nature of weathering and boulder exhumation, or a more complex nature of development where the largest clasts persist at the surface, both hypotheses which cannot be substantiated here. Considerable variation in basalt mineralogy has been shown (Tarawneh *et al.*, 2000). If this is the case, the temporal link previously suggested may purely be an artifact of basalt mineralogy, which coincidental with a temporal change related to basalt.

A direct link between geology, basalt age and the nature of the characteristic surface form found on each basalt is complex, and at times surprising. Within the Abed basalt surveyed in this study, a large diversity in slope profile forms has been identified. The influence of slope position has been shown, but significant levels of standard deviation in the results within each basalt type are apparent. The nature and variability of slope profile form and ground surface character warrants further description.

A systematic variation in ground surface cover down-slope has been established by aggregating results by plot position but a significant degree of variation which cannot be explained purely in terms of geology or basic slope variables is still apparent. Least squares correlation diagnostics between whole slope variables (length, height, ken.par) and surface cover variables, or their normalised transformations, yield only poor levels of significance. When the results are aggregated by whole slope, the only correlations of note are between slope length and Cv_b (r^2 = 0.229), roundness (r^2 = 0.06), crenulation (r^2 = 0.06), circularity (r^2 = 0.06) and perimeter (r^2 = 0.05), at 7 profile locations, but none of which are significant (significance values – α = 0.05 = 0.374, and α = 0.01 = 0.478). Whole slope angle yields equally weak correlations with circularity (r^2 = 0.04) and crenulation (r^2 = 0.05). Accordingly, slope height is poorly related to clast crenulation (r^2 = 0.05) and clast roundness (r^2 = 0.05). Grouping results by site location, and hence geology, appears unable to describe the nature of variability between plots. Disaggregating plots as independent points in the landscape yields a greater number of significant least squares correlations between slope variables and ground surface cover (Table 4.10). Here, each plot is considered independent, with its own local slope control.

The success of this method suggests that local controls on surface character are of great importance, in addition to the overriding significance of geology, previously shown. All variables return significant correlations, apart from the up-slope angle (the angle of slope length 10 m above the plot position). Ground surface cover, clast sorting, clast size and shape all relate significantly to both local (plot angle, slope curvature, plot distance down-slope, up-slope angle) and whole slope form variables (whole slope angle, ken.par, slope height, slope length). By regrouping the variables to individual plots significant correlations between slope and ground cover emerge. Local controls on form appear importance.

	Variable	Percentage ground surface cover	Cv_b	Mean intermediate axis length	Total clast edge length	Mean clast crenulation	Mean clast elongation
Whole slope variable	Plot angle	*0.397*	*0.413*	0.141	0.128	**0.561**	0.341
	Slope curvature	*0.404*	*0.390*	0.007	0.174	**0.685**	**0.608**
	Plot distance down-slope	*0.382*	**0.580**	0.058	0.137	0.108	0.038
	Up-slope angle	0.036	0.010	0.017	0.000	0.002	0.036
Local slope variable	Whole slope angle	*0.359*	*0.425*	0.164	0.174	0.174	0.033
	ken.par	0.107	0.002	**0.628**	0.001	0.280	0.252
	Slope length	0.257	0.312	0.362	*0.417*	0.041	0.000
	Slope height	0.003	0.026	**0.553**	0.025	*0.379*	0.300
	Whole slope angle	0.276	*0.425*	0.164	**0.553**	0.174	0.033

(significance levels: α = 0.05 = *italics*; α = 0.01 = **bold**)

Table 4.10 R squared values for least squares correlations between slope and ground surface cover variables

The strength of the correlations between surface character and slope implies that a gravity driven processes in this case hydraulics, are responsible for the condition of the contemporary slope surface configuration. The significance of the each correlation can be used to infer the nature of the dominant process in action. If both local slope and up-slope length or influencing area is equally strongly significant, then the implication is that hydraulic modification by overland flow is an important control on surface form. If slope or gravity, on its own, is most significant then the importance of hydraulics maybe less clear. Hydraulic action is controlled by both the slope of the point in question but is also conditioned by the angle and length of the up-slope area. If slope is significant and up-slope variables are not, then an alternative model of surface modification is more appropriate. An iterative alteration of surface form, via titling or toppling, the dominant direction of which is controlled by slope maybe more a appropriate mechanism of surface modification.

Hydrological processes both act and vary down the whole slope profile. If the significant correlations discussed above stand true, then the change in surface character down a slope profile should be closely linked to the form, or shape, of that profile. In this study the selection of profile locations with significantly concave, convex and rectilinear profile forms allows individual plots to be considered in the context of the whole profile. Even though the discussion below is concentrating purely on one example of each profile, the semi-quantitative method of profile location enhances the validity of any extrapolation from results generated from these sites.

The rectilinear slope profile was selected as a control location whereby down-slope variation in surface character can be examined independently from any slope form variation. The concave (CC) and convex (CV) profiles allows the examination of extreme profile forms in the spectrum of profile surveyed at Marab Swayed.

Rectilinear profile (ST)

The rectilinear profile demonstrates a down-slope variation of clast and surface form which indicates modification by surface processes (Figure 4.17). A long profile (> 200 m) was deliberately chosen such that absolute differences in surface form between plot positions would be clearly apparent, which is reflected below. Ground surface cover reduces down-slope but the difference between the Top and Middle plot locations is more pronounced than that between the Middle and the Bottom plots. The difference between plot positions is also notable in the values of Cv_b, which show a significantly lower value at the Top plot than at plots further down-slope. Mean intermediate axis length does not appear to follow a gradual change from Top to Bottom of the profile, with the Middle plot position showing the lowest mean intermediate axis length. The behaviour of mean intermediate axis dimensions maybe a reflection of the inadequacy of the measure in assessing surface character in respect to slope processes.

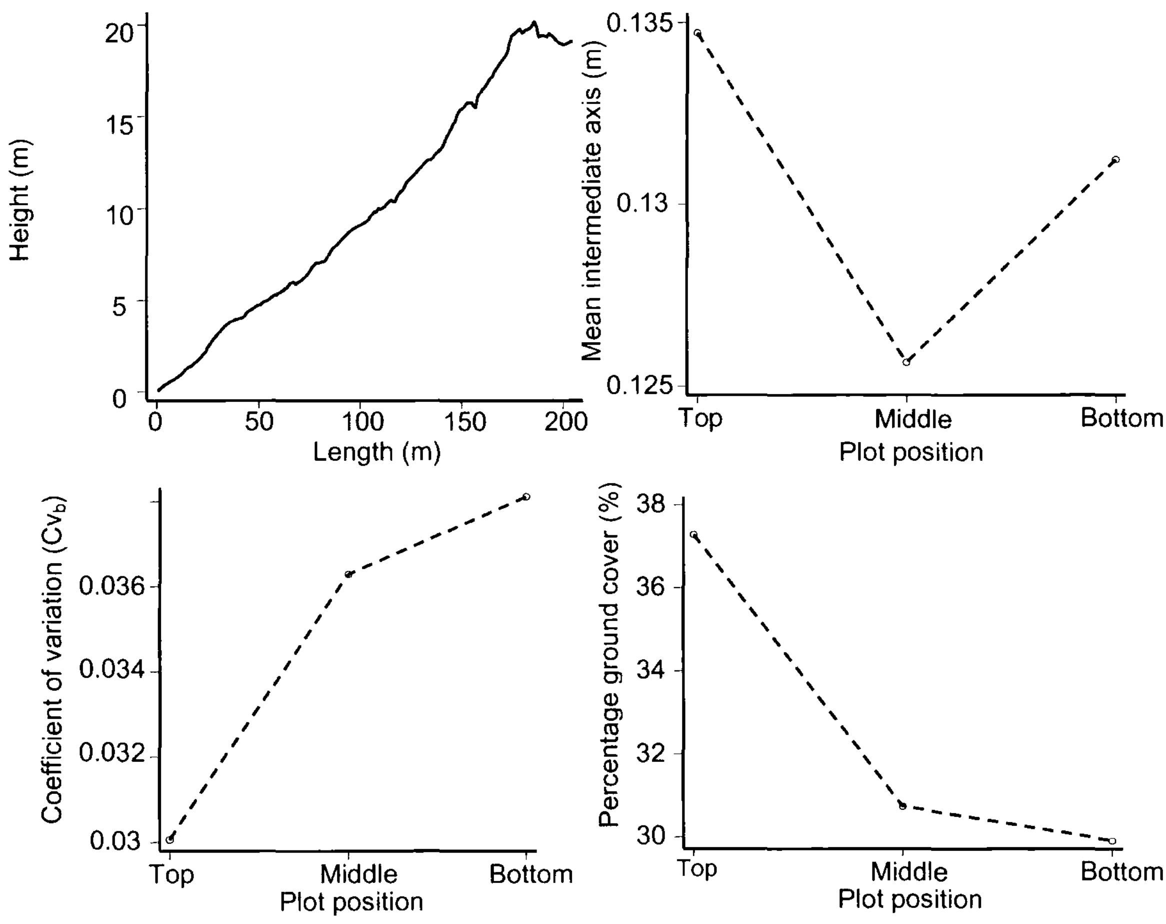


Figure 4.17 Ground surface variation – rectilinear slope profile (ST)

The nature of down-slope change suggests an increasing intensity of process action down-slope, attributable to an increased influencing up-slope area at the lower slope positions. The relative difference in surface character between plots can also be used as a surrogate for the variable action of surface processes. The change in surface character at the Middle plot is not halfway between the condition of the Top and Bottom plots. On a straight profile, if process intensity was linearly related to the volume of overland flow passing over each point, then the intensity of process action would increase linearly with distance down-slope as up-slope catchment area increases. Previously, a homeostatic link between form and process has been suggested whereby the ground surface cover acts to condition the processes acting on the slope, but not as yet tested in the northeastern Badia (Higgitt and Allison, 1998; Wainwright *et al.*, 2000). The nature of change on this profile supports this; percentage ground cover and the coefficient of variation appear to approach an asymptotic value down-slope, which may be a stable condition under which surface clasts control surface hydrology and its degree of surface modification. The interaction between form and process and potential feedback mechanisms in operation are discussed further below.

Convex profile – CV

Relative change in surface character down-slope on the convex profile in part adheres to the pattern of variability observed on the rectilinear profile. Ground surface cover reduces from the Top to the Bottom of the profile (Figure 4.18). In this instance a clear increase in clast population sorting is also apparent from slope Top to Bottom. The relative difference in surface character between plot positions is also of interest. There is a greater distinction between the Top and Middle, as opposed to the Middle and Bottom plots, with the latter exhibiting a similar level of ground surface cover and sorting. Due to the high slope angles at the Middle and Bottom plot positions the velocity of overland flow at the Middle and Bottom points may be greatest, accounting for an increase in sorting and a reduction in ground surface cover. Again, mean clast intermediate axis is greatest at the profile midpoint, suggesting that slope process action has little impact on down-slope clast size variation. The variation in intermediate axis can be considered as a result of variable process intensity down-slope due to increased volumes of overland flow. At the Middle plot overland flow is rapidly accelerating due to the break in slope angle, possible accounting for the apparently sudden drop in Cv_b and percentage ground cover.

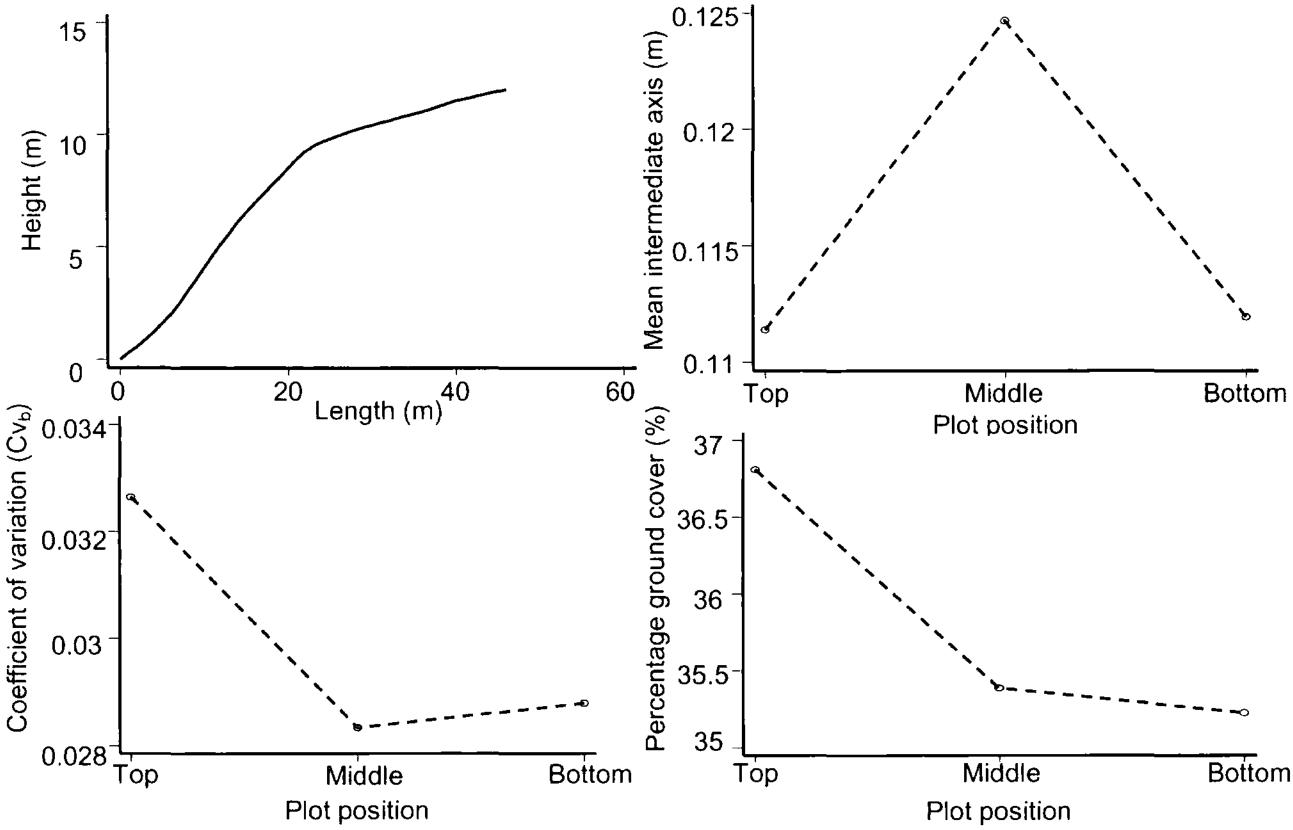


Figure 4.18 Ground surface variation – convex slope profile (CV)

Concave profile - CC

A systematic variation in ground surface cover on the concave profile is apparent. The variation of ground surface cover down the concave profile can again be explained as a result of the variable action of processes (Figure 4.19). Clast population sorting increases down-slope, but in this instance both mean intermediate axis and ground surface cover show a different nature of change down-slope. The largest mean intermediate axes dimension is found at the profile midpoint, as on the convex profile. Unusually on the concave profile a larger ground surface cover is found at the Bottom plot position relative to the Middle plot position. The relative influence of profile form can be used as an explanation. At the profile midpoint the plot is located in the concavity of the slope. Overland flow generated up-slope will have a high velocity, due to the high up-slope angle, and hence will have an enhanced erosive potential. At the Bottom plot location, where the slope angles are significantly lower, this erosive potential will be reduced. The tendency of clasts to move will be reduced. Hence the removal of clasts out of this portion of the slope will be lower than the transport of clasts in, increasing the ground surface cover at the profile Bottom.

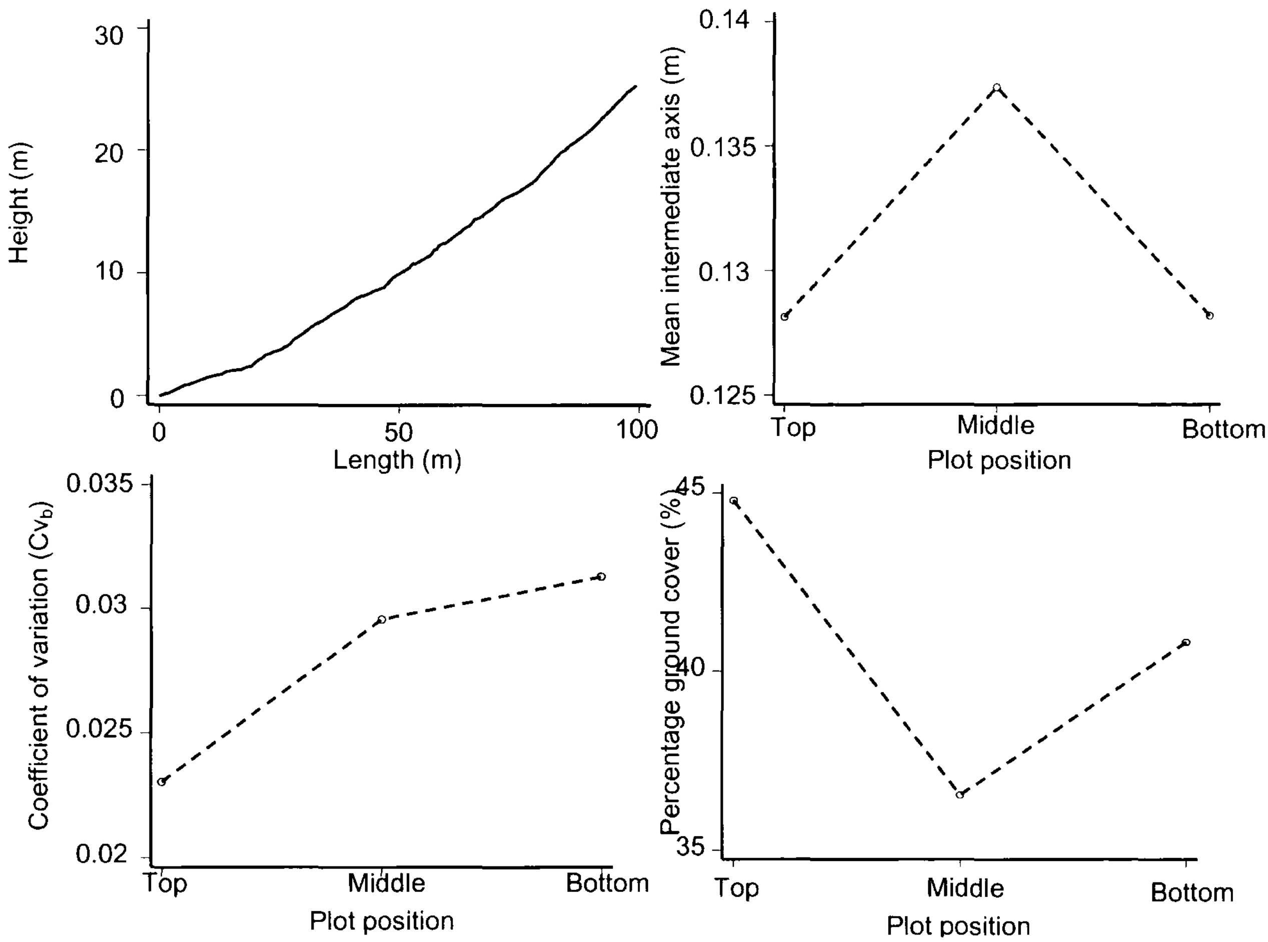


Figure 4.19 Ground surface cover – concave slope profile (CC)

Having noted a significant variation in form with slope and a seemingly diverse response of surface character relative to profile form, any conclusions about the control of slope form on surface character must bare in mind the likely mechanism of surface alteration. The above analysis focuses on the intensity of process modification of the surface, predominantly hydraulic processes, whose intensity is dictated by slope and up-slope area. Where the slope angles are highest the up-slope area is greater then the action of processes most intense. As stated previously the most feasible mechanism of surface modification is by an iterative process, whereby the cumulative influence of multiple small scale movements results in the variations in ground surface cover seen. Testing a hypothesis of hydraulic modification of the surfaces yields only insignificant results. There is no clear relationship between various slope variables and the ground surface character. Surface form variation suggests that the modification of the surface down-slope may approach some form of stable state. The slope character does not follow a linear variation from the Top to the Bottom of the profile but more normally approaches an asymptotic state. Although based only on three plot sample locations this pattern appears to be consistent. Conversely the standard deviation of many of the surface characteristics increases down-slope. The suggestion is that if slope process increases down-slope, the resulting surface modification resulting in a diversity of surface configurations, but these configurations are themselves at a stable asymptotic configuration.

4.4.3 Spatial characteristics

Observations in the northeastern Badia have noted pattern and structure in the arrangement of surface clasts. The presence and distinction of structure varies with position down-slope, indicating that this organization maybe controlled by slope process action. A structured surface may be more stable and enforce negative feedbacks on process action. For example a locked series of polygons constructed from surface clasts may act to inhibit overland flow. The low levels of significance in correlations identified between surface form and slope variables are not capable of reflecting the modification of process by form. No attempt to quantify or relate the presence of surface structure to the action of processes on clastic semi-arid slopes has been undertaken, either in the northeastern Badia or beyond. The only consideration of the spatial arrangement of surface clasts in the context of coarse clastic semi-arid surfaces has been qualitative (Abrahams and Parsons, 1994).

The presence of structure in landforms has been the focus of recent interest (Harrison, 2001). Structure is thought to be an emergent property indicative of self-organizing processes in natural systems (Phillips, 1999). In a model of self-organization, pattern is seen as both a cause and effect of process action and variability. The debate of self-organization in geomorphology has been limited to the lack of sufficient detail and depth of data to support quantitative models of self-organizing processes (Baas, *in press*). The image analysis allows the spatial character of the *in situ* nature of the surface to be assessed at both a high resolution and over a large spatial extent which encompasses a large sample size. The use of spatial statistics allows a quantitative assessment of spatial distribution of surface clasts and therefore surface organization. A quantitative comparison of structure between sites allows the presence and intensity of organization to be linked directly to other geomorphological aspects of slope morphology.

The range of spatial analysis techniques has increased as technological advances in data collection and analysis have developed. The lack of a statistical measure of similarity between 2-dimensional patterns often turns researchers to a qualitative description of pattern (Tribe and Church, 1999). A visual appraisal of similarity of structures and forms is therefore commonly relied upon (Tribe and Church, 1999). Spatial pattern is complex and methods of measurement vary between investigations with different objectives. An appropriate range of techniques have been adopted below to develop a transferable assessment of surface form between sites within the northeastern Badia. Pattern or structure firstly warrants further clarification. It is vital to consider the fundamental properties of pattern prior to trying to quantify pattern.

The nature of pattern can be indicative of process action. Equidistant spacing suggests repulsion between points, clustering suggests attraction and random spacing suggests no form of interaction (Evans, 1967). The distribution of separation distances between the neighboring objects can be indicative of the pattern of the distribution. A normal distribution of distances suggests random spacing, a peaked distribution implies regularity, a flattened distribution represents clustering. Evans (1967) proposed a tetrahedral model of pattern description in two-dimensional space. Pattern in two-dimensional space has four properties: regularity, clustering, linearity and randomness (Figure 4.20). Visually the surfaces of the northeastern Badia show linearity, some clustering and a regularity in clast distribution; the distinction of which commonly increases with distance down-slope.

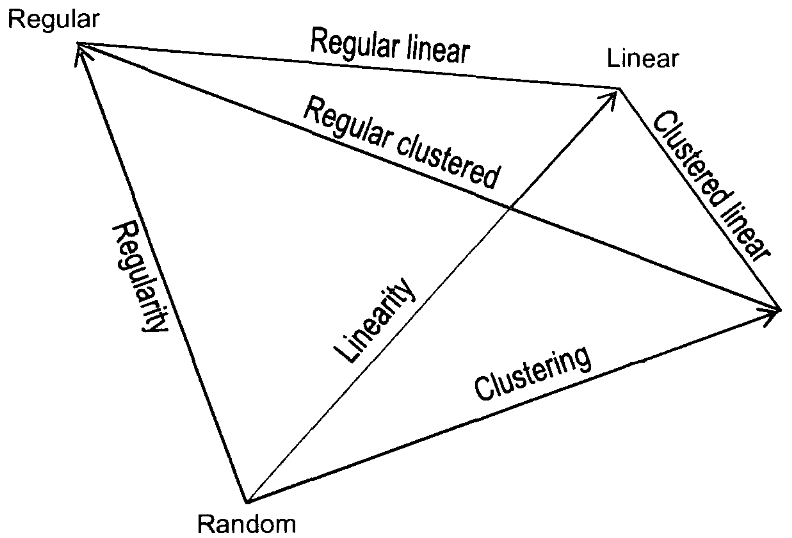


Figure 4.20 The description of two dimensional pattern (after Evans, 1967)

The distinct clasts on the open matrix surfaces of the northeastern Badia lend themselves to point pattern analysis. Several methods have been developed for the analysis of point pattern data in two-dimensional space and much attention has been devoted to its characterization (Diggle, 1983; Ripley, 1988; Fotheringham *et al.*, 2000). The objective of much of this work is to examine the degree and direction of departure of a pattern from complete spatial randomness (CSR). By definition the reduction of spatial data to a point pattern loses attribute information of each object within the pattern, for example clast shape or area. Point patterns are appropriate if the separation distances between points are far greater than the objects that the points represent (Okabe *et al.*, 1992). Furthermore, the need to sample a population often incurs bias and inaccuracy in the resultant estimated population characteristics (Greig-Smith, 1964; Berry and Marble, 1968; King, 1969; Pielou, 1975).

Geographical information systems (GIS) allow large numbers of spatially referenced data to be analyzed in a spatial context, minimizing the necessity for sub-sampling a large spatially extensive sample. Three approaches to understanding the variation in pattern and structure in the Badia are described below: nearest neighbor analysis; Theissen polygon analysis; and box fractal dimensions are used to describe the features of the patterns observed. Nearest neighbour analysis is designed to assess the degree of clustering. Additionally, a further spatially dependent measure of clasts form, clast orientation is discussed.

4.4.3.1 Nearest neighbour analysis

The image analysis combined with the DGPS survey derives the centroid location of each clast in WGS84 co-ordinates, to a precision of 0.01 m. Nearest neighbor analysis is undertaken in ArcGIS 8.1, using the Nearest Neighbour Script, v. 1.8[*] (Brooks, 1998). The resolution of the images means that up to the 8th nearest neighbor was commonly at only 1 pixel separation from the nearest 8 clasts, making the statistic meaningless. The analysis is therefore undertaken on all clasts greater than 0.05 m intermediate axis, which are separated by a distance greater than 0.02 m. The size threshold is also employed in the Theissen polygon analysis below for the same reasoning. Observation in the field indicates that structures are predominantly formed by the larger clasts on the surface, with smaller clast filling gaps in between, so the size filter does not bias the nature of the patterning measured.

Nearest neighbour analysis is undertaken initially on the binary overlay considering the planimetric projection of each clast. The most successful differentiation between plot positions is gained when the surface is reduced to a point pattern, despite the loss of clast specific data. The analysis assumes firstly that the area covered by each image is uniform, and that any variation is not a consequence of microtopographic variations in the

[*] download - http://arcscripts.esri.com/details.asp?dbid=10642

area itself but rather as a result of the interactions between the clasts in the image. Second, the area is considered to have an infinite extent, or at least there is no boundary that restricts the direction that clast separation distance measurements can be made. The effects of boundary conditions are reduced with the large point data sets used, but the effects can be corrected.

Measures of nearest neighbor distances are commonly employed to test whether a given distribution represents a random form or the departure of the distribution from complete spatial randomness (CSR). The ratio of the expected separation distance if the pattern were random, to the actual measured mean separation distance is commonly employed as a statistical measure of point pattern character (Fotheringham *et al.*, 2000).

The mean point to point separation distance in a random distribution is defined as follows.

Eq. 4.2

$$p(l) = 0.5d^{-0.5}$$

where: *d* is the density of points and *p(l)* is the between point separation distance. *d* is calculated as the total number of points in the unit area;

Eq. 4.3

$$d = \frac{N}{A}$$

where *N* is the total number of points in the image area (*A*). Combing Equation 2 and Equation 3 gives:

Eq. 4.4

$$p(l) = \frac{1}{2\sqrt{d}}$$

A comparison between 2-dimensional patterns is provided by the ratio of the mean observed separation distance $\bar{r}$ (l) and that expected for a random distribution *p(l)*:

Eq. 4.5

$$R(l) = \frac{\bar{r}(l)}{p(l)}$$

When R(l) tends to 1, the measured pattern approaches a random character. Statistically significant departures to non-random distributions are defined by:

Eq. 4.6

$$1.0 \pm z \cdot \sigma[R(l)]$$

where z is the standard deviate corresponding to the required level of significance, and σ is the standard deviation, defined below:

Eq. 4.7

$$\sigma[R(l)] = 0.5228N^{-0.5}$$

Commonly used values of significance for large point patterns give z = 1.96 for α = 0.05, and z= 2.58 for α = 0.01 (Fotheringham *et al.*, 2000). If the R(l) value generated falls either above or below these limits then the pattern is taken to be non-random. A pattern where all points are coincident returns a R(l) value equal to 0, 1 for a random pattern, and a pattern where points form a perfect lattice structure can be shown to return an R(l) value of 2.142 (Fotheringham *et al.*, 2000).

The majority of clast distributions from the 29 plots studied showed a significant departure to regularity, indicated by R(l) values > 1. Correlation analysis reveals no significant relationship between the R(l) value and slope or ground cover variables. The analysis of individual profiles reveals some degree of down-slope variation, but not at all sites (Figure 4.21). The Upper plot has a notable increase in R(l), and correspondingly Lower shows a marked decrease in R(l). The median value of R(l) increases slightly between Top and Bottom plot positions, suggesting a greater degree of surface organization of the clast surface towards the Bottom of the slope profile. The pattern of change is not however significant on all slopes surveyed, as seen in the high inter-quartile range at all sites.

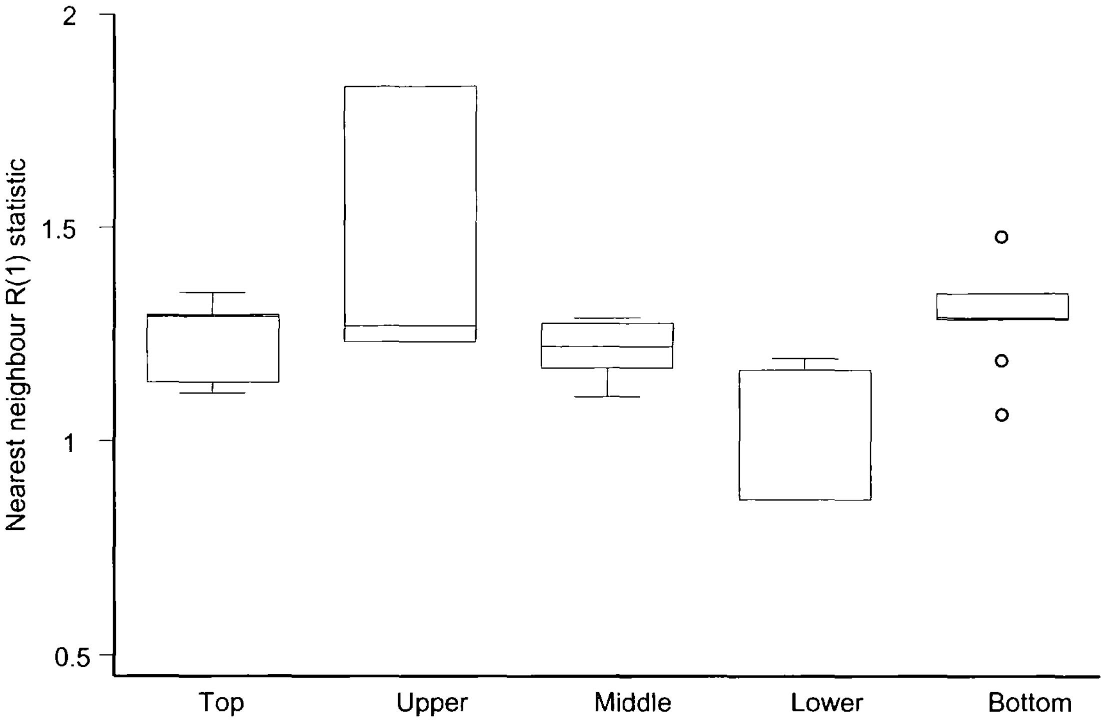


Figure 4.21 Down-slope change in R(1) nearest neighbour value

The analysis of nearest neighbor distances assesses clast spacing. Clasts spacing is both a function of clast size, and surface structure. At Top plot positions the large clasts size will increase and regulate the spacing between centroids. At Bottom plot positions the R(l) Analysis of R(1) values must however taken with caution. The R(1) distance, to the nearest neighbor, is, by definition, controlled clast size. Point patterns are generated from centroids of clasts. If the mean size of clasts on the surface is d, then separation between two clasts can be no less than:

Eq. 4.8

$$(2 \times \frac{d}{2})$$

Therefore, clasts cannot be clustered, as centroids will never be in close proximity. R(1) values therefore tend to suggest regular patterns. A consideration of higher order neighbors, beyond a separation of d, may yield a better understanding of pattern form, but this is beyond the capability of the nearest neighbor algorithm.

4.4.3.2 Theissen polygon analysis

Okabe *et al.* (1992) give a full discussion of the application of and background to Thiessen polygons in spatial analysis. Here, Theissen polygons are constructed around the point patterns generated from the binary overlays using the 'Thiessen' Arcscript within ArcView 3.1 3D Analyst extension* (Ammon, 1998). The surface patterns appear to be constructed primarily from the larger clast fraction, with the finer fraction infilling voids between larger clasts. A large number of small clasts in the Thiessen polygon analysis would act to heavily bias the results of the Thiessen polygon analysis. A comparison between tests including and excluding the small clast fraction showed that a greater statistical distinction between profiles and plot positions was achieved by excluding the finer fractions, supporting the use of this clast size filter. The clast size filter employed for the nearest neighbour analysis is used. Theissen polygons are computed such that the area defined by the polygon is closer to the enclosed point (the clast centroid) than to any other point in the point pattern, as described by Okabe *et al.* (1992) (Figure 4.22). The use of ArcView 3.1 GIS allows the rapid calculation of vertex number, vertex angles and Thiessen polygon area. Edge effects in the construction of the Theissen network are overcome within ArcView 3.1 by creating a buffer zone equal to 5% of the area contained within a convex hull draw around the extent of the point pattern.

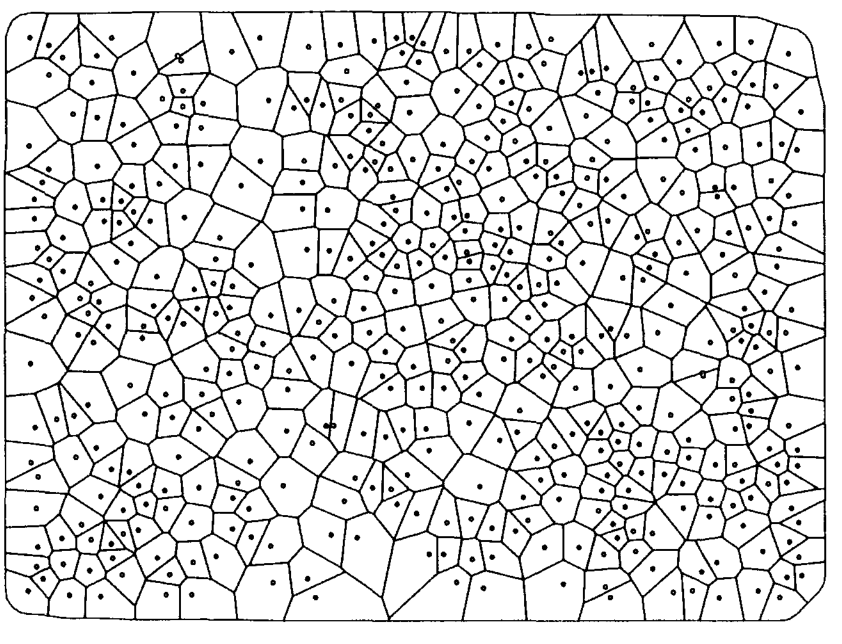


Figure 4.22 Example of Thiessen polygon net (SW1L)

* download: http://arcscripts.esri.com/details.asp?dbid=10107

A further sub-sample to minimize edge effects was taken excluding all points whose surrounding polygon was either on the edge of the pattern, or whose polygon form could have been influenced by an arbitrary edge effect (Boots, 1987). The most successful distinction of pattern and structured forms is found using the analysis of the standard deviation of the number of vertices in each polygon net (Okabe *et al.*, 1992). Thiessen polygon analysis allows a comparison between images of different dimensions, areas and scales. As the standard deviation of the number of Theissen vertices (T_{vert}) increases, the point pattern tends to clustering; and conversely a reduction in T_{vert} sees the pattern becomes more uniformly spaced. A consistent increase in T_{vert} down-slope is apparent suggesting a greater degree of regularity and clustering in the spatial arrangement down-slope (Figure 4.23). The Top plot position is notably less organized than the four down-slope plots. A larger interquartile range in T_{vert} is also apparent at the Upper and Lower plot positions.

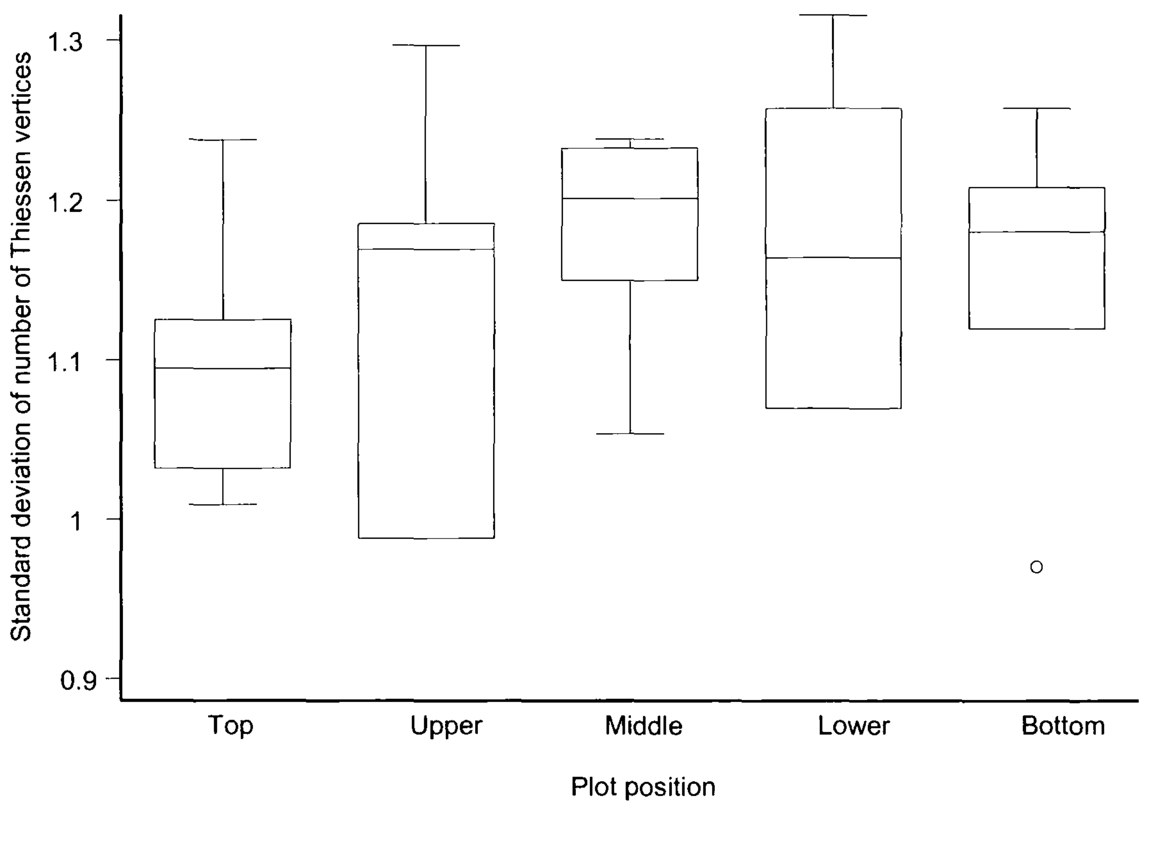


Figure 4.23 Variation of T_{vert} down-slope – all sites

As with the previous measures of surface character discussed, the aggregated statistics for all plot positions hide the subtleties in the data set. The examination of individual slope yields a more detailed understanding of down-slope variation. For example SW1 exhibits the general trend indicated by the aggregated statistics, with some notable exceptions (Figure 4.24).

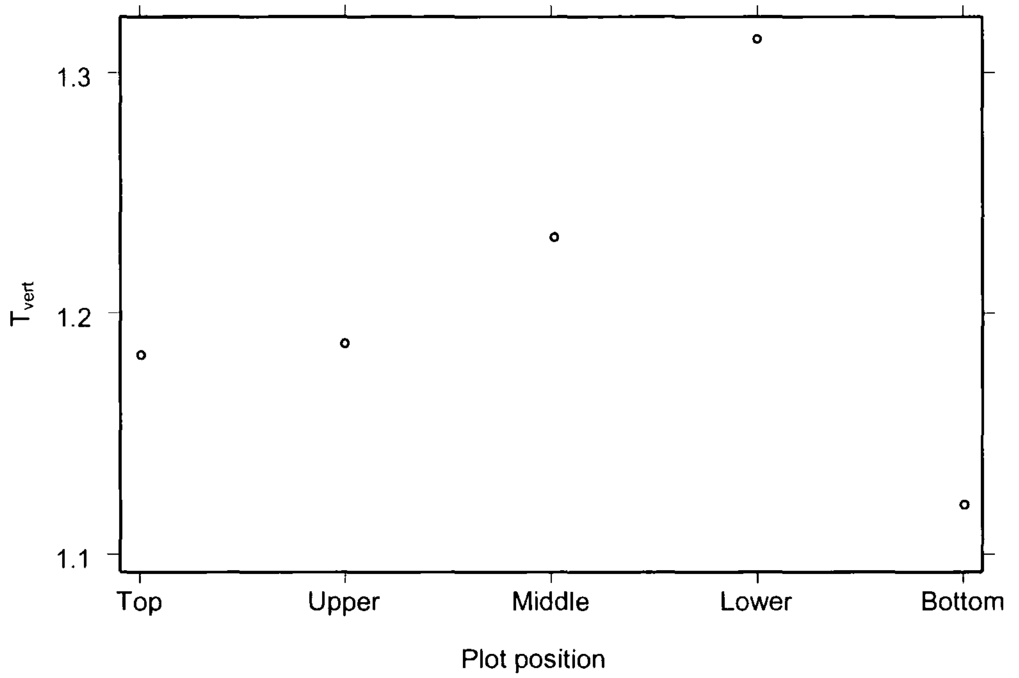


Figure 4.24 Variation of T_{vert} down-slope – SW1

Thiessen polygon analysis at SW1 shows an increase in clustering down-slope, represented by an increase in T_{vert}. Interestingly the bottom plot does not adhere to a gradual down-slope transition, showing an apparently marked reduction in the degree of surface organisation. An examination of the original images captured at SW1 suggests that at the Bottom plot position the low number of clasts limits the interactions and contacts between rocks (Plate 4.5). Structures cannot be formed as there is not sufficient density of cover of clasts. The implication is that structures arise from frictions between clasts. Where the low density of cover reduces contacts between clasts are limited and clasts are more free to move. The significant discrepancy between the Bottom plot position and the plots up-slope indicates that a threshold of cover may dictate the organization of the surface, below which structure cannot form. This threshold is clast size dependent.

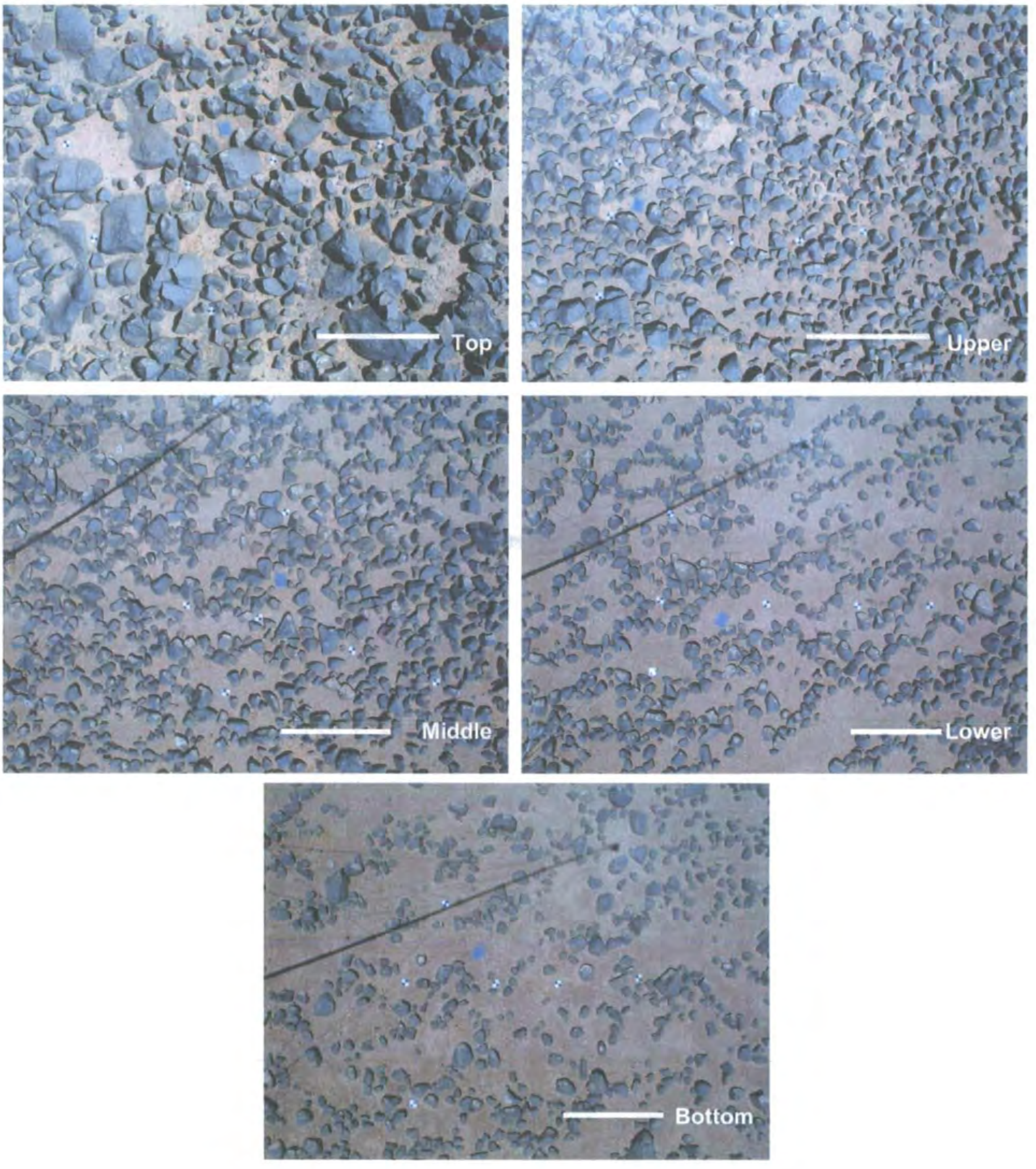


Plate 4.5 Down-slope change in the presence of surface pattern – SW1

4.4.3.3 Fractal dimension analysis

Observation in the field suggests that structure or pattern is a function of clast size. Surface with large clasts have large structures, whereas surfaces with smaller clasts have smaller structures (Plate 4.6). A scale free measure of structure or pattern would provide a measure of organization which is independent of the clast size distribution.

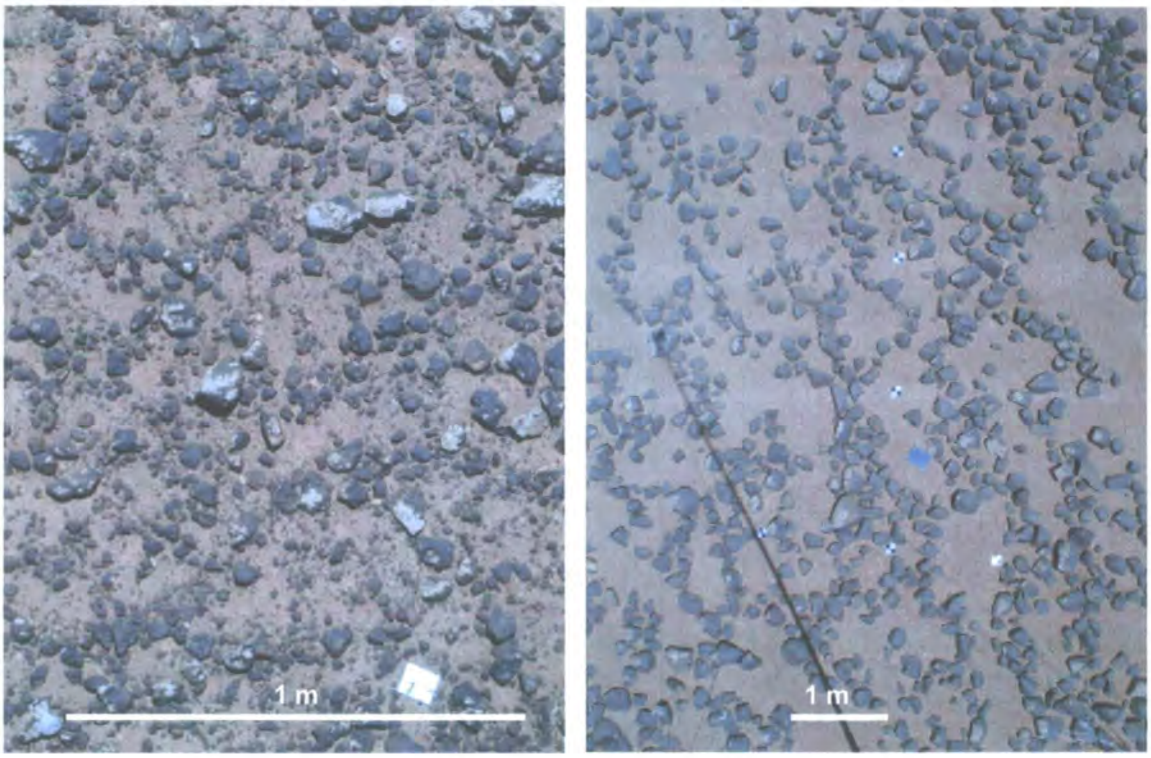


Plate 4.6 Pattern at different scales, with different clast sizes

Numerous examples of the use of fractals in geomorphology have been published including investigations into the fractal properties of landscape (Tingbao *et al.*, 1993; Rodrigues-Iturbe and Rinaldo, 1997), the structure of surfaces (Butler *et al.*, 2001), the fracturing of weathering rocks (Ehlen, 2000) and the geomorphometry of river planform (Stolum, 1998). Fractal dimension of semi-arid surfaces dominated by hydrological process has been identified. Dunne *et al.* (1992) in an assessment of surface roughness used the fractal dimension of a series of highly detailed contour profiles at set intervals down-slope, noting an increase in fractal dimension with distance down-slope. Fractal assessment of landforms is commonly regarded as closely linked to issues of chaos, self-organized criticality and emergence within geomorphology (Harrison, 2001).

The box dimension is used here as a measure of surface organization. Box fractal dimension is calculated for the sediment areas between clasts. The fractal dimension of the planimetric projection of clasts is constant, irrespective of spatial arrangement. Conversely the fractal dimension of the interclast spaces will vary with clast organization. Box fractal dimension was determined for the binary image overlays using custom written fractal slope analysis software (HarFA v. 4.0)[1]. An iterative process of overlaying the image with a grid of varying size and counting grid squares which totally cover the sediment area is used to determine box fractal dimension. Repeating this procedure with various sizes grid spacing (1/) results in a logarithmic function of grid size (1/) and number of boxes (N) needed to totally cover the object. The slope of the linear portion of this function, Equation 8 gives the box fractal dimension (F_{box}).

Eq. 4.9

$$\ln N\left(\frac{1}{\varepsilon}\right) = \ln(K) + F_{box}\ln\left(\frac{1}{\varepsilon}\right)$$

where; N = number of boxes

K = size of the box

F_{box} = box fractal dimension

A higher fractal dimension is generated when the interclastic voids represent a greater degree of self-similarity. Where there is a greater distinction between those areas that have and those areas that do not have boulders is more apparent. Where the sediment surface exhibits areas which are devoid of clasts the fractal dimension increases. Conversely where only small areas of the sediment surface are exposed and free of clasts the fractal dimension is low as the self-similarity between scales across the image is low. Fractal dimension may in part be a derivative of clast size distribution, for example a higher fractal dimension maybe expected from a surface with a broad clast size distribution. If the fractal dimension increases in parallel with a progressive decrease in the mean and standard deviation of the clast size distribution then the change in fractal dimension could be attributable to the clast size range. Conversely, if fractal dimension increases, but clast size remains constant or decreases in both mean and standard deviation, then the variation in fractal dimension must be as a result of spatial surface organization. This is found to be the case in the northeastern Badia (Figure 4.25).

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[1] http://www.fch.vutbr.cz/lectures/imagesci/harfa.htm

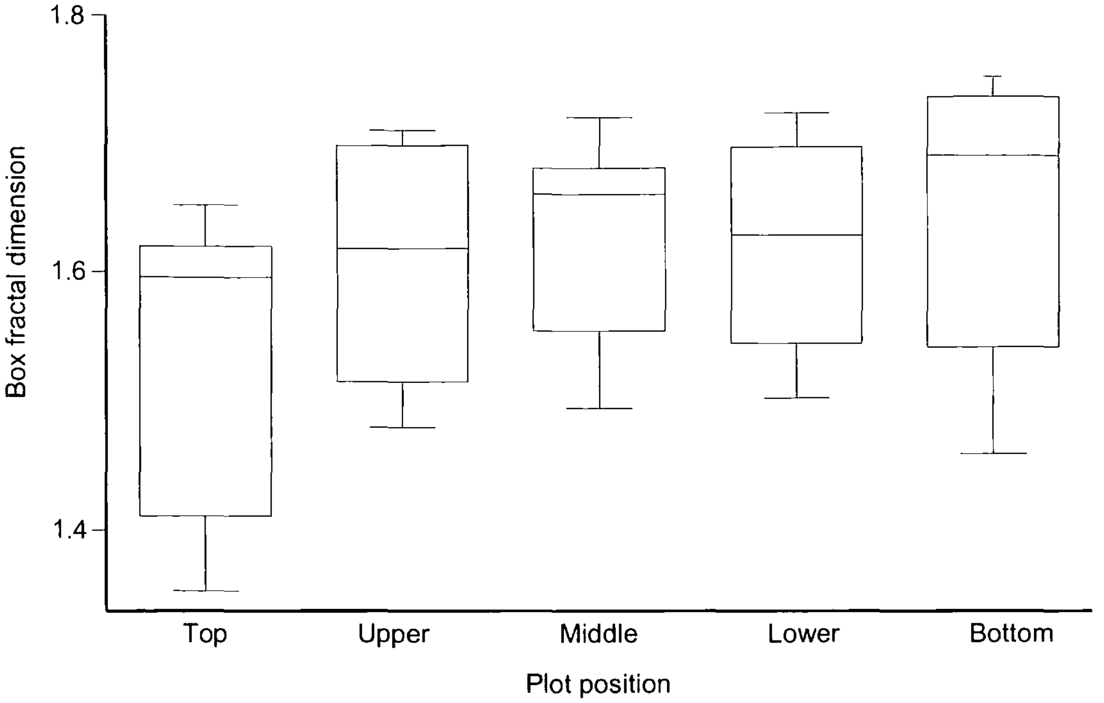


Figure 4.25 Down-slope variation in box fractal dimension

It is interesting to note that the analysis of box fractal dimensions shows a consistent down-slope variation in sediment area complexity with slope. Again an asymptotic relationship between distance down-slope could be suggested. Additionally, the standard deviation in box fractal dimension appears to decrease from the Top to the Middle plot positions and increase from the Middle to the Bottom plot positions. Again this may represent some form of divergent behavior down-slope.

4.4.3.4 Clast orientation

Preferential clast orientation has been examined on boulder mantled slopes as an indicator of overland flow process action (Vincent and Sadah, 1995; Ibbeken *et al.*, 1998; Friend *et al.*, 2000). In the northeastern Badia the preferential orientation of clasts may be used to aid the understanding of surface modification by slope processes. A preferential sorting across or down-slope may indicate alignment of clasts by flow processes. The *in situ* assessment of the surface provided by the image analysis generates centroid location and the position of the end points of the major and minor axis, from which clast orientation can be derived. Again the clast size filter (intermediate axis > 0.05 m) is applied to remove the smallest clast fragment. Orientation is more a function of the grid geometry rather than the planimetry of the clast shape for clasts below this size. Basic visual assessment of raw orientation data does not reveal the presence of modes in the data, and qualitative comparison of preferential orientation between sites is ambiguous (Figure 4.26). There is a tentative suggestion of four modes of orientation when the data is aggregated for all sites, focussed at 35°, 70°, 120° and 155°, relative to down-slope (0°), with a symmetrical distribution of orientations. Least square correlation yields only insignificant relationships between clast orientation measures, suggesting that there is no systematic variation across the landscape in clast orientation.

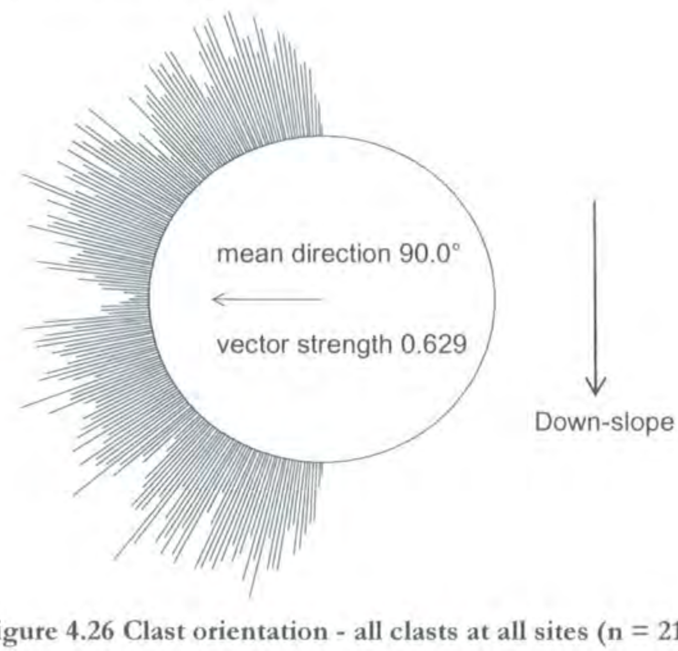


Figure 4.26 Clast orientation - all clasts at all sites (n = 21230)

A statistical technique is employed below whereby the distribution of clast orientations is progressively smoothed to an increasing degree, using a nonparametric density estimate (Fisher, 1993). As the level of smoothing increases, only the most significant modes or orientation trends are retained in the data. Mathematically the density estimate employed is described as follows:

Eq. 4.10

$$\hat{f}(\theta) = (nh)^{-1} \sum_{i=1}^{n} w\left(\frac{\theta - \theta_i}{h}\right)$$

where; θ = direction of clast orientation

n = each individual clast

h = magnitude of smoothing or kernel halfwidth

w(θ) = probability density function.

A probability density function with a bell shaped distribution with finite maximum and minimum limits is employed as the most appropriate to apply to circular data (Fisher, 1993). The chosen density estimate is based on a quartic smoothing function (Silverman, 1986) (Equation 4.11).

Eq. 4.11

$$w(\theta) = \begin{cases} 0.9375(1-\theta^2)^2 \\ 0 \end{cases} \qquad -1 \leq \theta \leq 1$$

The kernel density estimate was applied between 0 and 180° on clast major axis orientation data. The smoothing kernel width (*h*) was varied at 1° intervals between 1° and 50°. After each smoothing iteration the number of modes, defined here is a density estimate that is greater than both the estimate before and the estimate after, is calculated. The number of modes detected is then plotted against the width of the smoothing kernel, which gives a quantitative measure of the persistence or trend in clast orientation. The number of modes can then be identified to specific orientation angles in the smoothed data.

Analysis of the persistence of modes in orientation data does not reveal a conclusive pattern of down-slope clast orientation for all slopes or plot positions. At some profiles there is a suggestion of a greater persistence of a smaller number of modes in the data towards the toe of the slope at several profiles, for example profile CC (Figure 4.27). The asymptotic modal value decreases down-slope, suggesting a preferential alignment to a smaller number of orientations. The orientation of clasts at the Top plot position commonly stabilizes with between 6 and 3 modes (mean = 5.24), whereas the Bottom plot positions stabilize within between 1 or 3 modes (mean = 2.21). The preferential orientation of clasts is inconsistent. Modal orientations at Bottom plot positions tend to be either aligned across contour or down the slope profile. The vector strength of this is however insignificant. For example at SW2B, vector strength = 0.05, at an orientation of 002°, for a sample of 684 clasts (α = 0.05, significance level = 0.09). At other slope positions the orientation of clasts is far more constricted around one value. For example at STB, vector strength = 0.46, at 005.6°, for a sample of 534 (α = 0.05, significance level = 0.08).

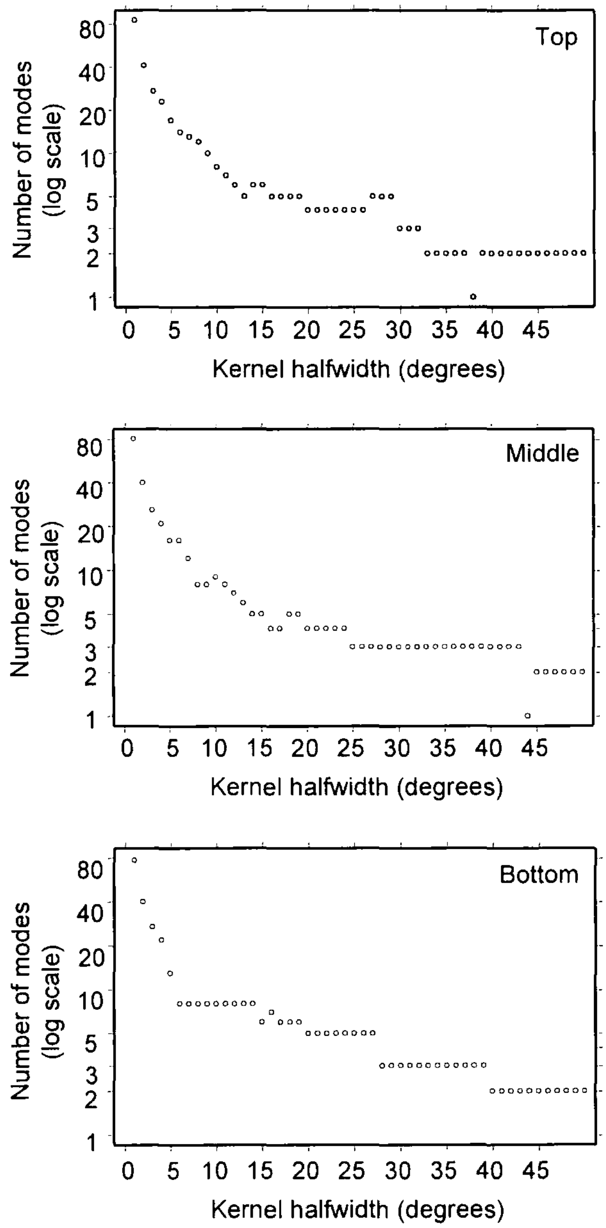


Figure 4.27 Kernel density estimate of the persistence of modes in clast major axis orientation – profile CC

The non-parametric density estimation reveals a greater degree of slope controlled organization, with a definite tendency for clasts to become more uniformly oriented about a smaller number of modal directions down-slope. There is however no systematic variation of the number or modes, or the orientations of the modes with slope or ground cover variables using least squares regression, for slope profiles or individual plots.

4.5 Discussion

The study of mantled surfaces provides little consensus on their origin and dynamics (Vincent and Sadah, 1995b). Broadly two hypotheses have been suggested. First, these surfaces result from fluvial re-grading over time (Rahn, 1967; Parsons and Abrahams, 1984). Second that mantles are relict weathering forms (Oberlander, 1974). A detailed study of surface character down slope profiles will allow the degree of surface modification by fluvial activity to be assessed. A wide range of morphometric data on various aspects of the form of boulder mantled slopes in northeastern Jordan has been presented. Significant relationships between the ground surface character and geology, slope and specific types of process have been established. There are a number of implications.

A large volume of evidence has been presented which shows a strong relationship between surface form characteristics indicative of slope process action. Particle texture and shape becomes progressively smoother and more rounded down-slope, implying that clasts undergo a greater intensity of weathering processes downslope. The results support a similar finding by Vincent and Sadah (1995), who identified an increase in clast rounding and sphericity down two pediment profiles in Saudi Arabia. Significant modification of the clast size distribution with distance down slope is apparent. The distribution tends to become more normalized, and more tightly constricted about a mean intermediate axis length. Surface form appears to be dictated by both the local context of the plot, supporting Cooke and Reeves (1976) proposition that “the inclination of a slope is related to the nature of debris generated on and carried across the surface”. The research in this study suggests that, in addition, both up-slope and whole slope controls on surface form are of equal importance.

The consideration of adequate measures of surface character has been shown in the northeastern Badia. Weighted means return more significant correlations than unweighted mean clast dimensions, strongly supporting the suggestions of Dunkerley (1996). The planimetric surface assessment allows actual characteristics of the surfaces, to which the weighted means approximate, to be directly quantified and notable similarities are apparent. Equally important are those measures of the surface which show no link to either ground surface cover, or slope properties. The measures include the unweighted intermediate axis, which is used as a standard coarse clastic surface measure. The widespread use of mean intermediate axis dimension as an indicator of slope form relative to process action therefore appears questionable.

Change down-slope in surface form is complex and often non-linear. The various characteristics assessed show a different pattern of down-slope variability. It is clear that there is distinction between the Top and Bottom plot positions and the Upper, Middle and Lower. The influence of bedrock outcrops and jointing structures as a control on surface form at the slope crest is apparent. Clasts at this location remain exposed to modification by weathering processes, but their size, angularity and lack of underlying sediments may restrict clast movement. The surface examined here present a similar situation to the boulder surfaces examined by Friend *et al.* (2000), where the surface is clast supported, and hence shows little modification via clast movement. At the profile toe, in addition to the formative influence of slope processes, a wider range of influencing factors maybe in action. For example increased aeolian deposition on the limits of sediment pans. Furthermore the low percentage ground surface cover commonly identified at Bottom plot positions is such that the behaviour of spatial character of the clast surface does not follow the gradual change in organization down-slope at the other four plots.

The nature of variability under several of the measures described appears to approach an asymptotic level, suggesting some tendency to surface stability. As distance down-slope increases, by definition the up-slope area and hence volume of overland flow collected increases. If surface modification is a direct function of the volume of overland flow the increase in surface modification would be expected to increase with overland flow volume. Instead a stabilization of the degree of surface modification has been detected, suggesting a negative feedback mechanism whereby the form of the surface acts to mute the action of slope processes. An example of this feedback has been shown through the analysis of the spatial nature of the surface character. Surface character has been shown to become more organized down the slope profile. The organization of the surfaces appears to be dictated by clasts becoming locked into nets and polygons. In a locked configuration the surface clasts are not able to move. Polygons are commonly oriented with their long-axis across the contour of the slope, forming step-like microtopography. A stable state balancing the degree of surface organization against the modification of the surface by overland may result in an optimum surface configuration.

The presence of a stable surface condition can be used to examine slope processes in action. The original hypothesis proposed suggests that the surfaces are altered by the iterative action of small scale adjustments in form, rather than as a result of catastrophic modification during large scale events. Logically on an idealized straight profile, overland flow volumes increase linearly down-slope. If the variation in surface modification does not mirror this style of increase, it is questionable whether overland flow processes are directly responsible for the variations seen. For example, if the dominant method of surface adjustment is as a result of heave processes due to shrink and swell cycles, then the variable intensity of overland flow will, to a point, have an influence. Heave processes rely on moisture entering the surfaces, to which overland flow will contribute. Saturation of the surface would mean that, irrespective of the increasing volumes of overland flow, the degree to which the surface can be modified reaches an asymptotic level. On the portion of the profile which does not experience saturation but has an increasing volume of overland flow, a gradual increase in surface modification could be expected. After the saturation point is reached then a more uniform degree of clast surface modification would be expected. Again various process are in action on the slope. Surface modification is multifaceted.

Surface modification appears to include a number of processes. First, the adjustment of individual clast form, through weathering processes. Second, the adjustment of the clast size distribution is apparent, which can be as a result of either the weathering out of the finer fraction, or the removal of clasts through transport by overland flow, or the mechanical weathering of clasts. Third, is the adjustment of the whole surface character, for example the movement of clasts into organized structure. The processes responsible for these types of modification are clearly as diverse as their influence on surface form. It is clear that a distinct variation these characteristics down-slope. Without field evidence and monitoring of real events the relative importance of for example overland flow as a mechanism of clast transport, or titling, relative to the displacement by a heave process is not clear. The nature of spatial variation down-slope implies a slope, and therefore hydrological control, on all of these processes. For example, during a rain event surface wetting may act to displace a clast, the resettling of which may produce a small down-slope movement. The movement of the clast may cause a collision between two clasts, acting to slightly modify the clast surface. The result of which is a slight reduction of percentage ground surface cover, an increase in the volume of underlying sediment, and a modification of the surface. Although this nature of change is very slight, the surfaces support a continuous cover of clast and represent a massive range of ages. Small scale change over a long period may therefore reasonably account for the variations in surface form seen today.

The nature of variability in results between plot positions also raises interesting questions with regards the evolution of the surfaces. The example of the percentage ground cover shows that the variation in ground surface cover is greatest at the slope toe, reducing up-slope. If the Bottom and Lower plots are considered to be more mature or more greatly modified surfaces, due to the presumably higher intensity of process action at these locations, then a divergence in landform development is seen. The surfaces do not tend to converge to one stable state but rather greater diversity in surface character is seen. Plot studies at Marab Swayed have all been undertaken on a uniform geology whereby the starting conditions are considered to be constant, such that any deviation away from this is considered to be a result of post-emplacement modification by surface process action.

Contrary to the evidence which suggests that the surfaces are divergent forms, there is also considerable evidence on convergence on these slopes. Clast sizes converge to a more uniform distribution, whereby the level of dispersion in sizes reduces. Additionally, clasts become progressively more rounded and more smoothed down-slope. Clast orientation and the departure from complete spatial randomness in clast position all appear to converge down-slope.

The influence of slope form has been separated from the influence of geology. A diversity of slope forms within one geology has a profound influence of the nature of surface character at various plot positions. Significant relationships can be found between the local characteristics of a plot and the configuration of the ground surface at that point. A greater level of understanding is gained from a whole slope consideration of the variation in ground surface cover. It is difficult to suggest a continuum of ground surface cover variation with a variation in slope form character given the limited number of profiles sampled in this study.

The influence of geology previously identified has been reiterated by the findings of this study. It is however clear that the degree of variation in surface form as a result of slope profile form variation is as equally significant as the control of geology on ground surface configuration. The link with surface age and surface character is less clear. Mean clast intermediate axis length appears to increase with age, contradicting much work on hydrology dominated surfaces, Poesen *et al.* (1990).

The spatial analysis of the surfaces provides the first insight into the organizational nature of boulder mantled surfaces. A systematic variation in surface organization down-slope is seen. The various methods of analysis adopted examine different aspects of the surface spatial character. The degree of self-similarity of clast organization, as described by the box fractal dimension, increases consistently down-slope. The use of the nearest neighbour analysis appears limited in described the complexity of the patterns identified. Surface structures are comprised of vertices commonly more than one clast in width. The nearest neighbour analysis is not capable of differentiating between linear clustering within the polygon vertices, and the wider form of the vertices. The Thiessen polygon analysis is more successful, identifying clear down-slope alterations in the surface form. Clast fabric, or orientation shows a marked down-slope variation, but no distinct alignment to or across slope can be identified. The spatial statistics have managed to identify trends in surface character that are not apparent in the other analyses conducted, and is hence of benefit.

Chapter 5: Hydrological processes

Chapter 5: Hydrological processes

5.1 Introduction

This chapter aims to understand the links between contemporary slope hydrology and surface form on coarse clastic desert surfaces. The chapter explores these links by examining the control of local ground surface cover and two-dimensional slope form on surface hydrology. Overland flow and hydraulic process are both critical controls on the removal and transfer of sediments on coarse debris mantled slopes (Bryan, 1922, 1940; Melton, 1965; Kirkby and Kirkby, 1974; Abrahams and Parsons, 1994; Roux and Roos 1996). The relationship between contemporary surface process and slope form is less well understood (Abrahams and Parsons, 1994). Abundant field evidence suggests that hydrological processes are the main contemporary geomorphological agent acting to modify the slopes of the northeastern Badia (Allison *et al.*, 2000) but the direct relationship between surface form, process and two-dimensional slope has not been addressed, either here or elsewhere. A homeostatic relationship between surface form and process activity has been suggested (Higgitt and Allison, 1999a). The objectives of this chapter are to highlight the nature of spatial variability in surface hydrology and in doing so to assess the relationship between the surface character and slope form.

The hydrology of the slopes of the northeastern Badia is poorly understood. No previous attempt has been made to look at the clast surface response to rainfall in the region. The ground surface configuration of the northeastern Badia limits the extrapolation of results obtained in other regions. The northeastern Badia experiences sporadic localized rainfall (Kirk, 1998). High magnitude, low frequency rainfall events dominate geomorphological change in the northeastern Badia (Allison *et al.*, 2000). The slopes are complex. The variation in surface character appears to reflect a diverse series of processes which act to modify the surfaces. Contemporary rates of surface modification appear to be slow. Direct monitoring of the processes of surface modification is therefore not feasible within the scope of this study.

This chapter firstly discusses and selects an appropriate method of process characterization, using rainfall simulation. A storm simulation experiment is developed which is designed to examine the degree of variation in surface response to rainfall across the northeastern Badia. The experiment design is based on local climatic records, field monitoring and previous simulation work, in addition to a series of trial experiments undertaken in the northeastern Badia. Replicating high-magnitude rainfall events is designed to identify any variations in surface response. The experimental design is deliberately constrained to the simulation of events that have been monitored in the northeastern Badia. The results are discussed in terms of the links between surface hydrology and surface form variation. The principle objective of this series of experiments is therefore to explore the linkages between contemporary slope hydrology and slope form, rather than to provide a comprehensive understanding of slope hydrology. In addition, the influence of two-dimensional slope form variation on whole slope hydrology is assessed. The diversity of data generated by the image analysis technique (Chapter 4) helps to demonstrate the apparently important controls on slope hydrology. The results demonstrate a close link between surface form and process action, which has numerous implications for the behavior and evolution of the northeastern Badia geomorphology.

5.2 Background

5.2.1 Previous work on hydrological processes on clastic semi-arid slopes

There is an extensive literature on the hydrology, hydraulics and sediment dynamics of clastic or rock fragment mantled semi-arid surfaces (Abrahams *et al.*, 1994; Poesen *et al.*, 1994). The presence of surface clasts can be considered as surface roughness. The influence of surface roughness remains a complex and vexing question (Römkens *et al.*, 2002). When considering surface roughness, the logical assumption is that an increase raises the resistance of soil to detachment by raindrop impact. Surface roughness also acts to increase the storage capacity of rainwater and reduces the velocity of runoff, lowering the erosive power of flow (Huang and Bradford, 1990). Conversely, it has been shown that on rough surfaces flow tends to concentrate, thereby promoting scour, headcut development and an increased tendency for rilling (Abrahams and Parsons, 1991; Helming *et al.*, 1997). The balance of positive and negative influences of surface roughness on slope hydrology is frequently site specific. The relationship is further complicated by the action of surface seal and crust development (Kirk, 1997) in addition to the antecedent soil water conditions (Torri *et al.*, 1999).

Studies of rock fragment covered surfaces have shown similar findings. Many researchers have identified that the presence of a rock fragment cover decreases the erosion potential, relative to an unarmored surface (Lamb and Chapman, 1943; Grant and Struchtemeyer, 1959; Jung, 1960; Dumas, 1965; Epstein and Grant, 1966; Meyer *et al.*, 1972; Box, 1981; Collinet and Valentin, 1984; Simanton *et al.*, 1984). This is attributed the increased protection of the surface from the action of rainfall, leading to a decrease in surface sealing, an increased rate of infiltration, a decreased runoff and a resulting decreased sediment yield. Rock fragment cover (Seginer *et al.*, 1962; Dumas, 1965;

Meeuwig, 1970; Box, 1981; Simanton *et al.*, 1984; Collinet and Valentin, 1984), rock fragment size (Grant and Struchtemeyer, 1959; Yair and Lavee, 1979; Wilcox *et al.*, 1988), rock fragment cover geometry (Koon *et al.*, 1970; Bunte and Poesen, 1994) and soil matrix properties have all been identified as influential controls on flow and sediment dynamics (Peosen *at al.*, 1994). Additionally, the position of rock fragments relative to the surface has been shown to be highly influential as a control on infiltration (Poesen *et al.*, 1990; Dunkerley, 1995).

The nature of variability in surface hydrology, specifically infiltration, in semi-arid areas has previously been demonstrated (Blackburn, 1975; Sharma, *et al.*, 1980; Yair and Lavee, 1981; Berndtsson and Larson, 1987; Johnson and Gordon, 1988). The variability in infiltration is mirrored in runoff generation (Smith and Herbert, 1979; Hawkins and Cundy, 1987). One property that is thought to dictate the degree of variability is surface character, specifically the presence of rock fragments (Abrahams and Parsons, 1991). Hydrological processes have been cited as one component in the creation and maintenance of desert pavement surfaces (Roux and Roos, 1986). Several studies have highlighted the importance of overland flow and raindrop impact in modifying surface form (Roux and Roos, 1986; Wainwright *et al.*, 1999). Linkages between studies of rock fragment covered surfaces and specific types of desert mantles or pavements are more limited. The majority of these influencing factors vary considerably in the northeastern Badia (Allison *et al.*, 2000). There is a need for surface hydrology to be assessed on the coarse clastic surfaces in the northeastern Badia of Jordan to gain a more comprehensive understanding of the regions geomorphology.

5.2.2 The use of rainfall simulation to examine hydrological processes in semi arid areas

Rainfall simulation has been used to study runoff generation, infiltration and sediment dynamics in a diversity of environments. The technique has been applied to a wide range of pedological, hydrological and geomorphological situations (Duley and Hays, 1932; Young and Burwell, 1972; Bork and Rohdenburg, 1981; Bergkamp, 1998; Cerda, 1998; Foster *et al.*, 2000; Wainwright *et al.*, 2000). Rainfall simulation has many advantages as a method of understanding surface hydrology. The interaction between sediment and water can be studied over a short period of time under highly controlled conditions both in the field or the laboratory. With control over amount, intensity and duration, in addition to drop size parameters (Coutinho and Tomas, 1995), energy characteristics (van Dijk *et al.*, 2002) and water chemistry (Borselli *et al.*, 2001), experiments can be undertaken to elucidate subtle levels of variability in surface hydrology. The control of intensity, energy, drop-size and duration, at least, is required for successful rainfall simulation (Meyer, 1958). The technique has several advantages over other methods of quantifying surface hydrology, many of which stem from replicating a natural events or processes.

The unpredictable, infrequent and random nature of storm events in the northeastern Badia makes the real-time study of their influence on the landscape virtually impossible. To be successful extensive instrumentation of whole catchments would be necessary (Wainwright *et al.*, 2000). Despite the infrequent nature of storms, it is often those with the most infrequent return interval that are the most influential on the landscape (Kirk, 1997). Rainfall simulation is not an exclusive tool that removes the need for monitoring real events. Both should ideally work in tandem to gain a combined understanding of landscape process, an approach adopted below.

5.2.3 Rainfall simulator and the choice of appropriate equipment

There is a broad range in the design and principles behind rainfall simulation and only recently have attempts been made to standardize methods between investigations (Parsons and Lascelles, 2000). Rainfall simulators fall into two broadly defined categories, defined by the method of rain drop formation. The choice of simulator is dependant on the ability to accurately recreate rainfall characteristics repeatedly. The aerial cover of simulators ranges from the small infiltrometer with an area of only 0.15 m diameter, to the large scale experiments using, for example, the 'EMIRE' Rainfall Simulator, covering an area of 5 m by 10 m (Esteves *et al.*, 2000). The first category of simulator, based on a spray nozzle for drop creation, operates at high pressure and provides a wide range of drop sizes with high kinetic energies sometimes in excess of natural rainfall (Battany and Grismer, 2000). Stationary spray simulators tend to produce a conic distribution of rainfall intensities to the plot (Hall, 1970), whereas simulators which employ a rotating nozzle have an unavoidable periodicity in rainfall application which results in a notable variation in response of the surface (Becher, 1994). The second type of simulator employs drop formers, which include yarns, hypodermic needles, nylon cord and plastic tubes, all of which operate under lower pressures. They tend to produce a more tightly constrained distribution of drop sizes. Under this method of drop formation the kinetic energy of drops is entirely determined by the rainfall drop height.

Several specific characteristics of rainfall simulation were required for this study, which ultimately dictated the choice of simulation method. The main constraint on experimental design was the subtly in variation of clast surface form. It was assumed that the variation in surface hydrology will be equally discrete. Therefore precision and consistency in the replication of the characteristics of natural rainfall between experiments was of paramount importance. There are only limited existing data with regard to the drop size distribution, maximum intensities and durations of storm events in the northeastern Badia. Attempts to gain a more detailed understanding of the drop size distribution and storm characteristics in the northeastern Badia are discussed below. The ability to replicate the natural rainfall in the northeastern Badia with the chosen rainfall simulator was of vital importance. Equally a consistent distribution of rainfall across the plot between experiments is imperative. Without a uniform rainfall distribution across the plot the influence of the spatial distribution of surface clasts can be examined. The northeastern Badia frequently experiences high winds throughout the day (Kirk, 1997). A method of restricting the influence of wind on the rainfall drop area is therefore necessary. Finally, the storm simulation developed uses a diverse range of rainfall intensities.

The specific requirements for rainfall simulation described all favor the use of a drip screen rainfall simulator. Its compact design is easily transportable, rainfall parameters are highly consistent between experiments (Holden, 2000) and water efficiency is good (Bowyer-Bower and Burt, 1989). Wind can be shielded and precise changes in intensity can be made rapidly. The small plots that this method uses (0.5 m^2) are a potential limitation of this technique when trying to overcome the influence of small scale heterogeneity in surface character. It is recognized that spatial variations in surface form maybe overly reflected in a plot area of this size, but the use of several contiguous plots within close proximity means that local heterogeneity can be assessed and accounted for within the results.

5.3 Experimental design

5.3.1 Characteristics of the rainfall simulator design

A simulator based on the design described by Bowyer-Bower and Burt (1989) and Robinson and Naghizadeh (1992) was employed for this study (Figure 5.1). The success of the design is reflected in its frequent use by many workers (Imeson and Verstraten, 1986; Bowyer-Bower, 1993; Foster *et al.*, 2000; Holden, 2000). The simulator design was modified for this study and field site conditions. Due to the large range and magnitude of intensities of rainfall required, a pump driven water supply replaced the mamometer previously used for generating the required intensities. This allowed rapid and precise changes in intensity during the storm simulation. Analysis of drop size distributions using both the mamometer and pump system revealed no discernable difference between the two methods of water delivery. Ground surface temperatures in the northeastern Badia had a range of over 50^0C during the day, which altered the air pressure in the mamometer, water tanks and drip screen. The flow gauge and pump allowed much greater regulation and control of this effect. The range of intensities required cannot be achieved on the mamometer without replacing the regulating pipe during the experiment.

Drops formers were constructed from Tygon tubing of 0.0023 m outside diameter and 0.007 m inside diameter, though which a 0.025 m length of 0.006 mm nylon was threaded and crimped secure (Figure 5.1). In total 627 drop formers in 19 rows of 33 covered an area of 1 × 0.5 m at an even spacing mounted in a Perspex tank with inside measurements of 1 × 0.5 × 0.008 m. Each drop former was checked prior to each experiment to ensure that it had not become blocked or dislodged in transport. A 0.004 × 0.004 m galvanized wire mesh was hung freely 0.2 m below the drop formers to randomize the drop distribution. This meant that theoretically a maximum drop size of 4 mm could pass though the mesh. Water was held in a 25 l tank on the ground. Water was taken from the only local water source, a shallow ground water aquifer at Tel Hassan, Azraq. The source was kept constant between experiments. The effects of water chemistry are recognized (Barton, 1994) but in the field site location there is no feasible access to a distilled or rain water supply. The same water supply was used for all experiments.

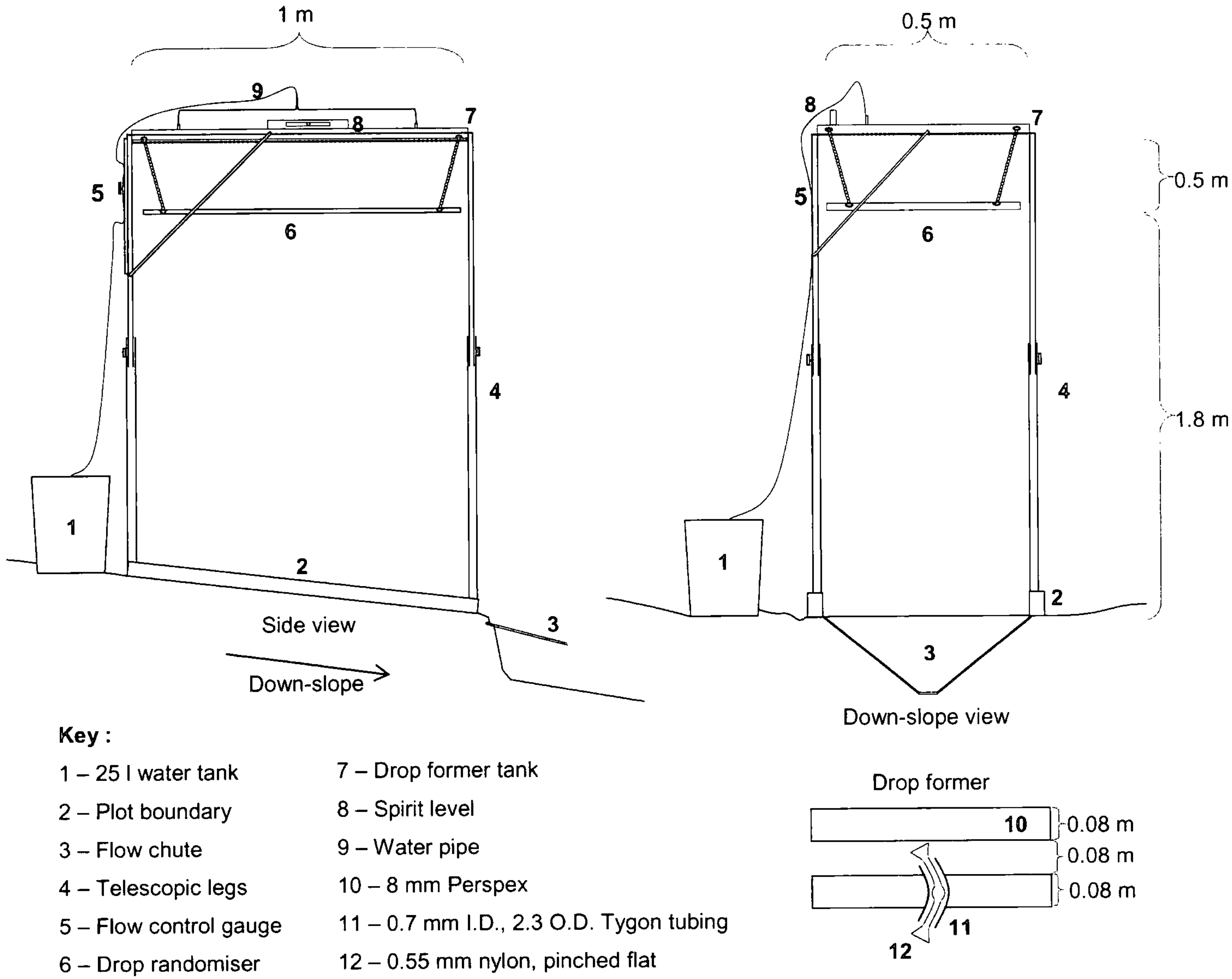


Figure 5.1 Rainfall simulator design

Placing the water tank on the ground provided greater stability to the simulator in high winds, which meant that a greater drop height could be achieved. The simulator was anchored to the ground using tensioned steal cables. Drop height from the central point of the drip screen was kept constant at 1.8 m from the randomizing screen to the ground. A re-circulating pump system, based on that described by Batteny and Griser (2000) regulated flow to a range of 5 mm h^{-1} to 140 mm h^{-1}. Calibration tests showed that a given intensity could be recreated within ± 2 mm h^{-1}. A selected flow rate on the flow gauge (Figure 5.2) correlated well to the desired intensity, calculated from the output generated. Water pressure was provided to the drop former tanks by a 12 V automotive fuel pump. Fuel-pumps were found to give a very regular and stable discharge and run from a standard car battery for a full day in the field. A fuel-pump has the disadvantage that they are self-lubricating in that the fuel they pump oils the pump mechanism. The pump ceases to work after pumping water for a long period, so required frequent drying and oiling. A flow gauge and three-way bleed tap allowed precise control on flow rate (Figure 5.2). The pump set-up also removed the need to keep pressurized constant head water Mariotte reservoirs.

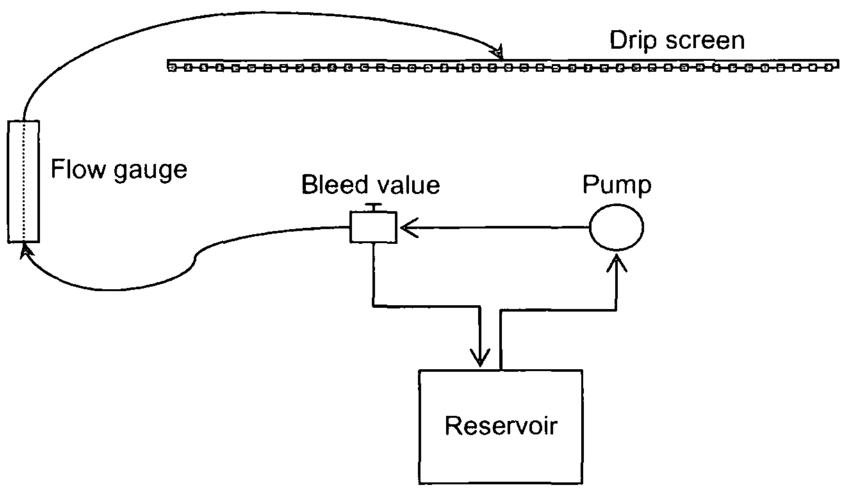


Figure 5.2 Rainfall simulator water pump system

The drop zone was shielded from wind and sunlight using a thick woolen canopy and corrugated plastic sheeting. Intense sunlight on the plot surface increased evaporation, so each plot was fully shaded to maintain consistency between experiments. The drip screen was supported in an aluminum frame such that the drop height could be adjusted level on plots of various angles.

5.3.2 Field plot design

The location of plot positions is designed to assess local heterogeneity in addition to the influence of whole slope form variation (Table 5.1). Results when combined with those generated from the surface characterization, can be assessed by any ground cover, slope or hydrological variable, in addition to grouping by profile or plot position.

Slope	Position	Plot position name	Number of replicated plots
ST	Top	STT	3
	Middle	STM	3
	Bottom	STB	3
CC	Top	CCT	3
	Middle	CCB	3
	Bottom	CCM	3
CV	Top	CVT	3
	Middle	CVM	3
	Bottom	CVM	3
		Total	27

Table 5.1 Rainfall simulation plot locations

Plots were constructed the day prior to the experimental run. As a result the presence of the plot did not alter the surface to any significant degree. Plots were bounded with concrete walls approximately 0.2 m high and 0.075 m wide, such that the inside dimension of the plot was exactly 0.5 × 1 m. The up-slope end of the plot was not bounded. Concrete was molded over clasts and into cavities which crossed the boundary, without disturbing the surface. The density of clast cover almost without exception meant that plot boundaries traversed clasts. Where the bounding wall rested on the sediment surface it was buried approximately 0.03 m beneath the surface, without disturbing the plot area (Figure 5.3). This reduced lateral loss of water during experimental runs. The concrete was left to air dry over night but shaded to limit cracking. The outside of the plot wall was also packed with damp sediments during the experiment to further reduce lateral water loss.

Figure 5.3 Experimental plot (left) and plot lip (right). Scale marker is 0.1 m square

The plot lip was constructed using concrete. Figure 5.3 shows the detailed structure of the lip and runoff collection tray. The highly friable sediments were prone to collapsing both during the construction of the lip and during the experimental run. During initial trials water was found to seep back and beneath the concrete lip, rather than continuing over the surface and down the flow chute. The best method of lip construction involved a sharp step, approximately 0.3 m deep being cut vertically into the sediment to 0.6 m in width, centered on the plot. A wooden casting mould was positioned vertically 0.2 m in front of the step and liquid concrete poured into the void behind it. Once the concrete was tacky the cast was removed and the aluminum runoff chute was pressed into the concrete to leave an indent and overhang. The plot lip was left to dry overnight, the day prior to the experiment. During the run the seal between the tray and the lip was waterproofed with petroleum jelly and silicon gel. The contact between the lip and the sediment surface was smoothed to ensure that it was water tight. Each plot used approximately 30 kg of concrete and 25 l of water to construct. A hole below the lip was dug to house the runoff chute and runoff sample bottles.

5.3.3 Rainfall characteristics of the northeastern Badia

The design of the rainfall simulation is based on rainfall characteristics both previously observed and recently monitored in the region. By far the majority of rainfall events in the Badia do not generate overland flow (Kirk, 1997). The cumulative effect of low intensity rainfall events on surface geomorphology is poorly understood, whereas the action of high magnitude events is more evident in the field. In order to assess the levels of spatially variability in surface hydrology, the rainfall simulation was designed to force runoff generation though storm simulation. The rainfall parameters used to design the experiments employed in this research are taken from the northeastern Badia. Additional data from beyond the region are discussed for comparison. The limitations of climatic data are recognised as a limiting factor in dictating the design of the experimental set-up. Present rainfall data from the Badia does not record maximum intensity, drop size distributions or storm durations (Kirk, 1997).

The highest resolution regional weather data available are hourly records for stations administered by the Water Authority of Jordan (WAJ) and the Meteorological Department. Automatic weather station (AWS) data for the winters of 1992/3 and 1993/4 monitored rainfall at 15 minutes intervals (Kirk, 1997). The published rainfall intensity graphs for Jordan are based on hourly records (Kirk, 1998). Field observations imply much higher intensities than suggested by published data (Kirk, 1997). For example, Kirk (1998) describes a storm of 42 mm h^{-1} on 18th December, 1993 (14 mm in 20 minutes). AWS data suggests that the highest storm intensities lie between 40 and 60 mm h^{-1}, but that the majority of rainfall events comprise between 0.5 and 5 mm, which according to the rainfall intensity diagrams published gives intensities of only 1 – 15 mm h^{-1}. Kirk (1998) suggests that storms rarely last for more than 30 minutes; therefore much of the published data is not representative of the storm events in the northeastern Badia.

Evaporation rates during summer months are in excess of 7.5 mm (Kirk, 1998), giving a very strong negative water balance. This reduces to less than 5 mm per day in autumn months, increasing the likelihood for a positive water balance. Kirk (1998) noted the high degree of both annual and seasonal variability in rainfall totals. A standard deviation of over 45% of the mean annual rainfall total is commonplace across the region. Over the longer-term three gauges studied by Kirk (1997) show a more stable picture of annual rainfall totals, averaging between 67.3 to 76.1 mm. Analysis of the magnitude and frequency of storm events, using data generated from an AWS by Kirk (1997) shows that the majority of storm events total less than 5 mm of rainfall. Conversely in high rainfall year storms may frequently generate more than 10 mm of rainfall in one event. High magnitude events are seen to occur towards the beginning of the wet season, whilst the remainder of the season is dominated by much lower intensity, more frequent storms, totaling 0.5 mm to 2 mm only. Kirk (1998) points out the danger in making generalisations from such a localised sample. The presence of Jebel al-Arab (Jebel Druz) is a key topographic control on the nature rain storms. Rainstorms in the region are sporadic and unpredictable (Kirk, 1997). The data suggests that there are some events with very high intensities but with return intervals of a number of years which can potentially have the greatest influence in modifying the landscape (Hudson, 1961; Kowal and Kassam, 1976; Dorn, 1994).

5.4 Monitoring of storm events in the northeastern Badia

The maximum resolution of storm data previously collected is 15 minutes (Kirk, 1997). The data is too crude to give a detailed understanding of short, intense rainfall events. The localized nature of convective storm cells mean that formative events are rarely recorded by the limited number of gauges installed in the region. Some attempt to rectify this was made during the six month field period at the start of 2001, whereby every notable storm that occurred during the field period was recorded. A sampling interval of 1 minute was used to describe the nature of rain storms in more detail than previous monitoring had allowed. Drop size samples were collected using the flower pellet method for each storm monitored (Bentley, 1904). This, combined with various previous studies from neighboring regions, was used as the basis for the simulation of the northeastern Badia rainfall. The monitored storms were five events with a rainfall total in excess of 10 mm, collected between 10.01.01 and 20.06.01. The storms reflect a very wet year in the northeastern Badia. Data from local gauging stations in the northeastern Badia do not correspond to the monitored storms. Timings of neither storms nor rainfall totals match the data recorded at the permanent monitoring sites in the northeastern Badia, showing the inadequacy of the spatial cover of the monitoring network to measure intense localized storm events.

A series of manually operated rain gauges were set up in the grounds of the Safawi Field Center and the Marab Swayed field site. Rainfall was collected in three traps, each of 0.28 m diameter. The collected rainfall was manually siphoned and volumes measured at 60 s intervals. Durations of storms ranged from 14 to 47 minutes and rainfall totals ranged from 10.7 mm to 27.3 mm (Figure 5.4). Within each storm there was a large variation in the intensity of the rainfall. Storms often followed a pattern of slight rain, followed by heavy intense rain, and then a final period of less intense rain. Figure 5.4 gives one minute resolution intensities for each of the five storms recorded. Maximum intensities recorded were of the order of 100 mm h^{-1} but this period of intensity only occurred over a limited period of no greater than 10 min within the monitored storms.

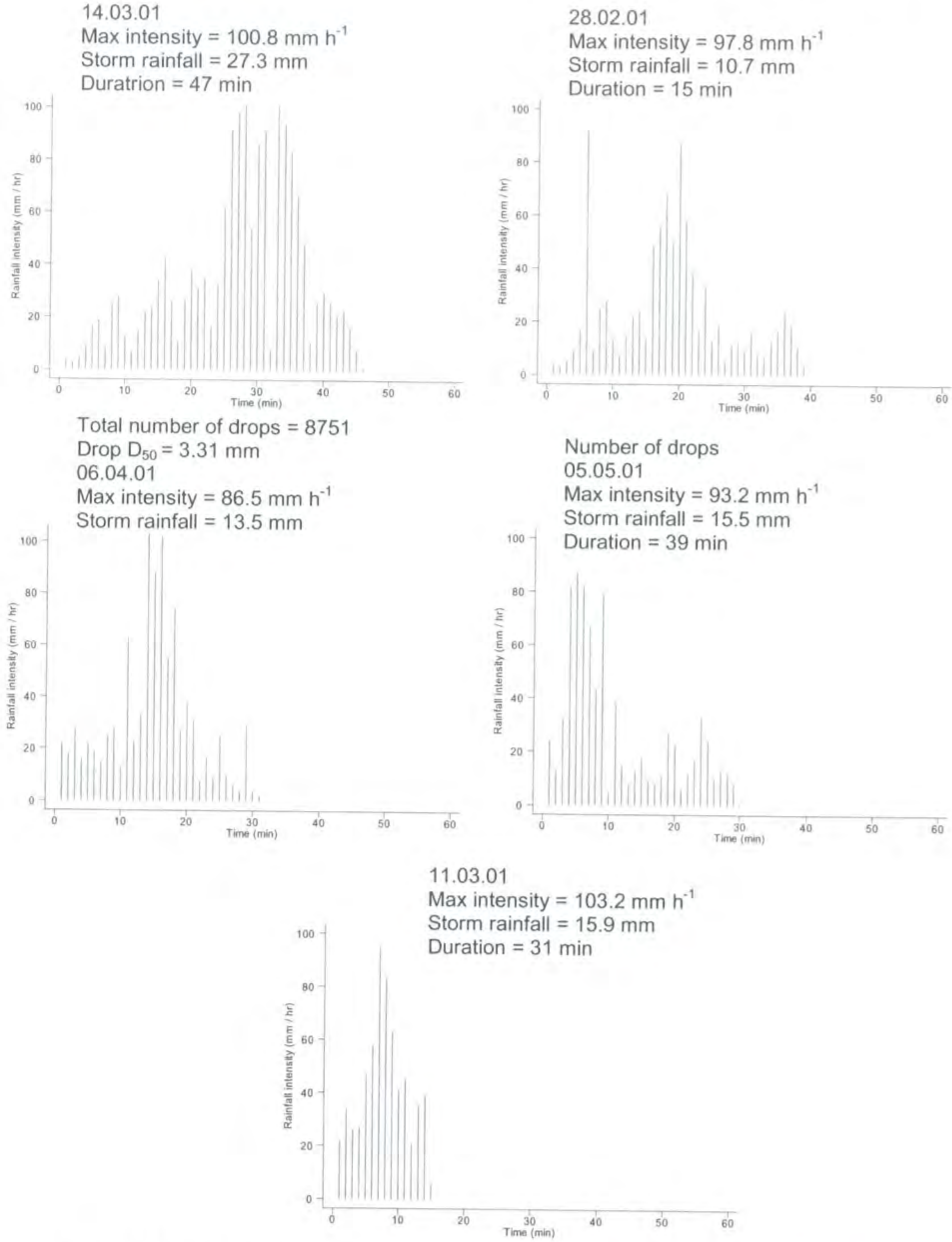


Figure 5.4 Individual rainstorm events monitored in the northeastern Badia (10.01.01 – 20.06.01)

Drop size data was collected during these storm events using the flour pellet method (Holden, 2000) (Figure 5.5). Pellets were collected in trays with a total surface area of 0.25 m^2. Trays were exposed to rainfall for 20 s and then oven dried at 105°C for 4 hours. A total of over 8500 drops were collected from the 5 storms. The sample also covered a wide range of intensities and drop sizes at different rainfall intensities.

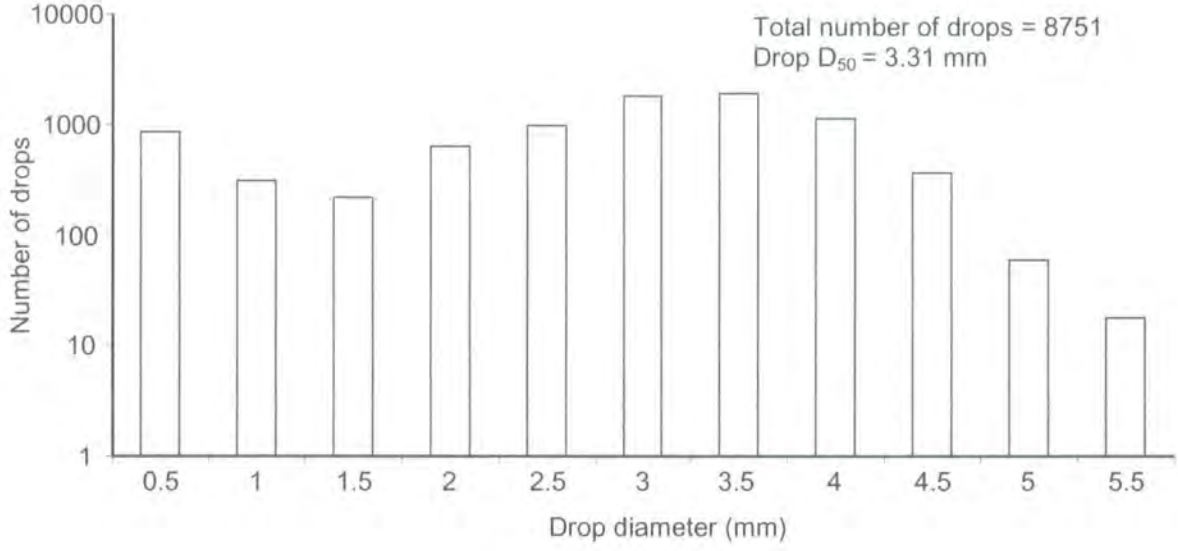


Figure 5.5 Drop size distribution from monitored storm events in the northeastern Badia

The data collected suggests that the D_{50} of the sample collected was 3.31 mm, within a broadly bimodal distribution of drop sizes. The maximum drop size recorded was 5.7 mm. The measurements collected compare favorably with data collected from neighbouring regions that experience convection cell rainfall such as the Negev (Kidron and Pick, 2000).

5.4.1 Semi-arid storm events beyond the Badia

To ensure that the rainfall monitoring undertaken in the northeastern Badia generated reasonable data, the results were compared to similar studies in the Middle East and other desert environments. There are numerous documented examples of large infrequent rainstorms and associated flood events in dryland environments, several in the Middle East (Greenbaum *et al.*, 1998). The role of infrequent cellular convective storms is seen as critical component of slope hydrology in the Negev (Greenbaum *et al.*, 2000). Storms in the Negev tend to be sourced in either the Red Sea Trough (RST), or the Mediterranean. The Mediterranean storms bring mean intensities of 15 mm h^{-1}, with peak values of 45 mm h^{-1}. The RST storms are characterized by localized convective cells between 10 km and several hundred kilometers in area, occurring mainly in autumn and spring. The storms have high intensities, with a mean of 60 mm h^{-1}, maximums of 120 mm h^{-1}, causing major flood events (Greenbaum *et al.*, 2000). The highest maximum rainfall intensity was reported by Lange *et al.* (2000), at the Nahal Zin experimental catchment, at 224 mm h^{-1}. Only 5% of storms in the Nahal Zin catchment generate overland flow and runoff. Small rainfall totals monitored during such storm events, of between 12 and 19 mm do not reflect the magnitude of subsequent flood events. The disparity between the monitored rainfall and the observed flood reflects both the highly spatial and temporal nature of storm events. High intensities rarely last for more than 8 minutes in the Negev (Kidron and Yair, 2001). Rainfall totals vary by up to six times over a distance of only 150 m within a convective storm cell. The local diversity in rainfall demonstrates that a low number of disparate low resolution rain gauges would neither identify the durations or spatial extent of such events. Beyond the Middle East, other authors have noted a similar style and concentration of rainfall events. Osborne and Renard (1969) studying at the Walnut Gulch experimental catchment in southeastern Arizona, noted the relatively high probability of high magnitude events. Bull *et al.* (2002) note the importance of high magnitude events in an intensely monitored catchment in southeastern Spain. The storms monitored in the northeastern Badia, are therefore comparable to those found in neighboring and similar regions.

5.4.2 Design of experimental storm

No previous rainfall simulation experiments have been undertaken on boulder mantled surfaces. Prior to experimental design, a series of trial field experiments were undertaken as a reconnaissance, using both single and multiple rainfall intensities. The results demonstrate several factors which influence the design of the storm simulation. Firstly, considerable local variation in times to runoff and ponding are noted between plots separated by only short distances. Sediment yields are low for all intensities (< 0.004 kg m^{-2} h^{-1}), including intensities above 60 mm h^{-1}. Infiltration is low, requiring rainfall intensities of roughly 6 – 7 mm h^{-1} to generate standing water. When runoff commenced, a stable state was quickly reached under constant rainfall intensity. An example is shown in Figure 5.6, where a simulated rainfall intensity of 60 mm h^{-1} is mirrored by runoff generated from the plot.

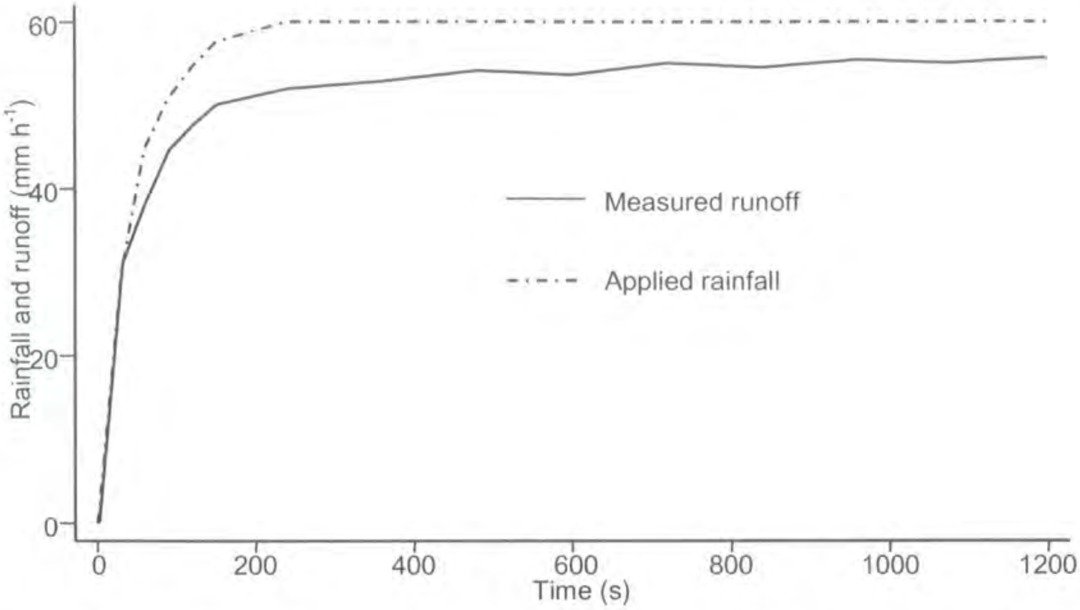


Figure 5.6 Adjustment of runoff to applied rainfall during a 60 mm h^{-1} rainfall simulation

The observations from the trial experiments have several implications for the experimental design. As Kirk (1998) suggests, in considering the nature of rainfall which has the most effect of erosivity, it should be the period of maximum intensity that is of interest. Using high intensity rainfall also *forces* the surface to respond. Processes under a high intensity rainfall will be at their maximum, such that any difference in response should be equally exaggerated. Conventional studies employing rainfall simulation tend to use single or small numbers of discrete intensities in separate experiments. With the available data from monitoring local storms, a simulation of a whole storm event is possible. This has numerous advantages above simulating single intensities. First, a storm simulation is more representative of a natural event. Sequencing of periods of variable intensity rainfall has a profound effect on soil moisture antecedence. Undertaking a very high intensity rainfall simulation on a dry surface may give unrealistic values for sediment removal. Many of the observed and documented examples of storm events note the light to medium rainfall prior to the highly intense storm maximum. Second, several previous studies have undertaken a series of increasingly intense rainfall simulations, with a recovery period in between events. From the storm monitoring it is clear that no such period between changes in intensity exists under normal conditions. The lack of control over antecedent conditions between experiments in the diverse temperatures of the northeastern Badia, is a potential source of inconsistency.

The choice of a single intensity for simulation is often arbitrary with little quantitative justification for the selection of that value. A simulation of a storm event approximated to one recorded in the field is hence of no less value. This method is perhaps particularly appropriate to the surfaces in question. Trial experiments have indicated that the surface rapidly reaches a stable level of runoff generation during rainfall, reflected in sudden changes in runoff when intensity is either increased or decreased. Due to the precise nature of rainfall generated by the simulator, any known change in the application of rainfall can be subtracted from the response of the surface with confidence. A model storm hydrograph was therefore developed (Figure 5.7).

Applied rainfall intensities were selected from the storms monitored by others (Kirk, 1997) and those within this study. The duration of the storm was kept constant at 2100 s, with three distinct periods of rainfall. An initial 600 s period of 17.5 mm h^{-1}; 600 s of 100 mm h^{-1}; finally a 900 s period of 60 mm h^{-1} (Figure 5.7, fine line). The intensities were all previously found to instigate runoff after 180 s, 48 s and 112 s respectively. The actual simulator output was assessed during the simulator calibration, where the rainfall fell onto steeply inclined corrugated plastic sheeting and channeled into a measuring cylinder, recorded at 30 s intervals. Some lag times are apparent, especially during periods of increasing rainfall intensities, but less so during decreases in intensity. Lag times are attributed to the pressures equalizing between the pump and drop former tank, and the time for the runoff to drain from the collection sheet to the measuring cylinder. Stable intensities are achieved and maintained rapidly and could be obtained to a precision of ± 2 mm h^{-1}. The lag-time for the rainfall simulator to adjust to the changes in intensity meant that the output from the simulator was more complex (Figure 5.7, dashed line). The actual simulator output (Figure 5.7, dashed line) was used in the calculations of runoff and surface hydrology. Total rainfall for the simulated storm is 34.6 mm, which over the 0.5 m^2 plot, is roughly 17.3 l of water.

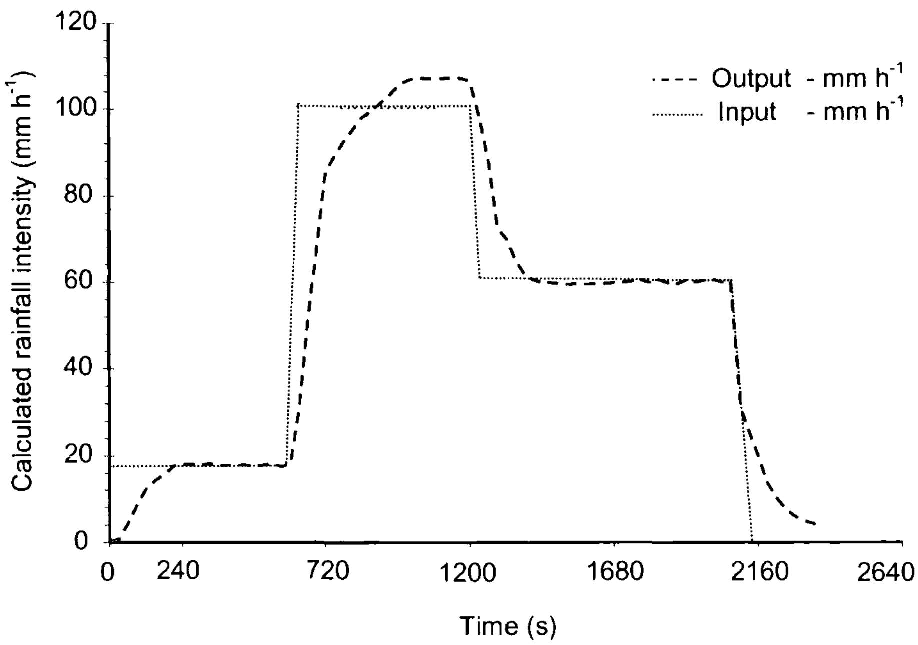


Figure 5.7 Simulated rainfall hydrograph

Drop size distribution and rainfall energy calculations were undertaken for the simulated storm using the flour pellet method. Mean drop size increased with intensity (Figure 5.8), but leveled off after 70 mm h^{-1} at a mean D_{50} = 2.6 mm. Mean drop size is less than that measured in the field. The distribution of drop sizes generated by the drip screen is preferential to alternative methods of rainfall simulation.

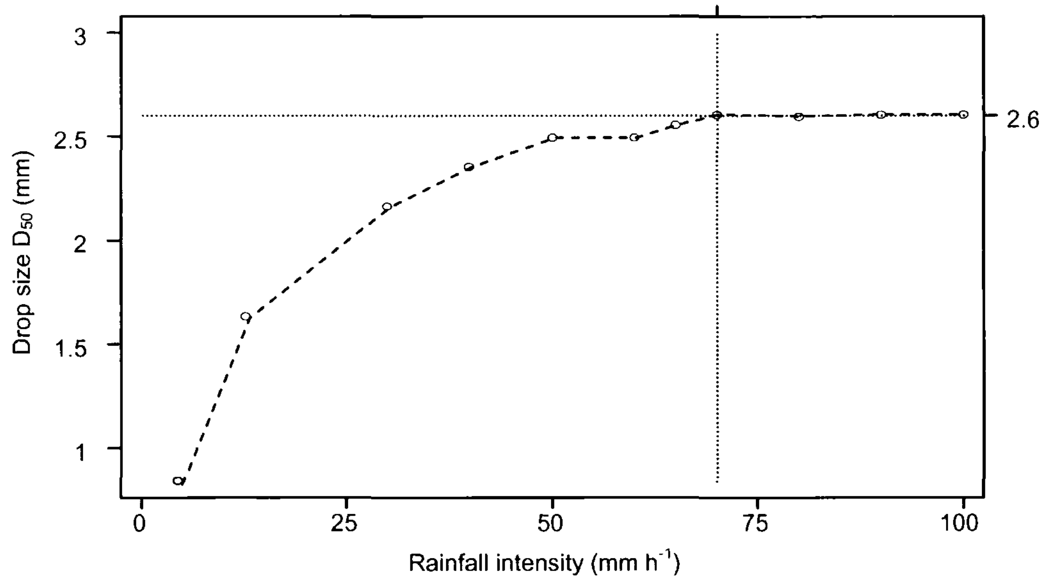


Figure 5.8 Relationship between drop size D_{50} and simulated rainfall intensity

The mean rainfall kinetic energy was calculated. The drip screen mesh height was maintained at 1.8 m above the ground for all simulations, although on steep plots this height was obviously variable. At the mean intensity of the storm event simulated (51.5 mm h^{-1}) represents a mean kinetic energy of 1.05 × 10^{-3} J m^{-2}s^{-1} for a drop size with D_{50} = 2.6 mm (van Dijk *et al.*, 2002) representing 68% of the kinetic velocity of rainfall at terminal velocity, and 64% of the naturally occurring rainfall in the northeastern Badia. Laws (1941) proposed an ideal drop height in excess of 9.4 m. Laws (1941) suggested that for drops of 2 mm in diameter a drop height of 5 m was required and drops of 3 mm required a height of 7.2 m to reach terminal velocity. The range of terminal velocities from the rainfall simulator employed here, given the limited fall height, is of the order of 60 – 95% of that of natural rainfall. More severe erosion due to splash impact may be expected under natural conditions.

The uniform application of rainfall to the plot was assessed by placing 20 beakers on the plot and measuring water collected at a range of intensities. The distribution was highly sensitive to the tank being level. Care was needed during the set up of the rainfall simulator. No systematic variation in rainfall application was noted across the plot.

5.4.3 Experimental procedure

One rainfall simulation experiment was conducted per day at the plot positions. Experiments were conducted before 11 am and after 2 pm to avoid the intense temperatures during the middle of the day which were found to increase evaporation from the plot, in addition to flexing the Perspex drop former tank. The rainfall simulator is shown in Plate 5.1

Plate 5.1 The rainfall simulator in the Badia

During each experiment runoff samples were collected from the flow-chute attached to the down-slope end of the plot. The flow-chute was coated with petroleum jelly and angled such that runoff and sediments flowed into the sample bottle. Sampling started as soon as runoff commenced. Samples were collected for a period of 30 s, every 30 s until runoff ceased at the end of the experiment. Ponding time, time to runoff and time to completion of runoff from the start of the experiment were recorded. Each experiment generated around 30 runoff samples. Bottles were pump filtered though Watman Grade 1, 61 mm filter papers, air dried and wrapped in aluminum foil for transportation back to the UK. In the UK loss on ignition was undertaken on the samples (BS 1377, 1990). Filter papers were ashed and the burnt weight subtracted from the sediment mass which was calculated on a five figure balance. Particle size analysis of the sediment samples, where possible, revealed no distinct pattern or variation in granulometry either during or between experiments. Mean particle size was 46 μm (standard deviation = 54 μm), with D_{16}:D_{84} ranging from 0.18, to 0.0315 for 37 sediment samples. Particle size analysis was hampered by the low levels of sediment collected (mean sediment load for over 1000 samples = 0.06 g).

5.5 Results

The results are presented in three sections. First, the general characteristics of infiltration, runoff generation and sediment dynamics from simulated rainfall in the northeast Badia. As the first series of rainfall experiments in the northeastern Badia these experiments provide a valuable insight into the hydrological response of the surfaces. Second, the control of the coarse clastic ground cover on slope hydrology and sediment dynamics is examined. The results are then extrapolated to a whole slope understanding of the relationship between surface configuration and process variability. Third, a discussion of the results is presented, which draws together the data generated form the image analysis and the surface hydrology experiments to gain a greater insight into the controls on slope dynamics.

5.5.1 General observations

The rainfall simulation produced a diverse response in surface hydrology between locations. Infiltration and runoff generation rates varied considerably between both disparate and contiguous plots. Low levels of rainfall instigated runoff, though generally significant runoff was only noted shortly after the onset of intense rainfall. Runoff is Hortonian Overland Flow (HOF). The nature of surface wetting was dictated initially by the shelter afforded to the surface by clasts, whereby overhangs sheltered areas of sediment from raindrop impact. Standing water quickly developed in microtopographic depressions and was often confined or dammed by clasts. Little or no clast surface storage was noted due to the rounded convex and varnished nature of the clasts. Rainsplash tends to transport surface particles (> 2 mm) which concentrated in the sheltered zones around the clast perimeters.

Runoff was generated on all 27 experimental plots. Runoff developed when standing water breached the boundaries of depressions and flowed either down though the plot or out over the plot lip. Runoff was continuous but fluctuated and in some cases appeared to closely mirror changes in rainfall intensity. Through the course of each experiment a larger proportion of the plot area contributed to runoff and areas of standing water coalesced. Sediment yields were generally very low. No hydraulic deformation of surface sediment, for example scour, was noted within the plot. Fine surface organic matter was initially transported from the surface and then in places some fine surface sediment became detached as flow paths developed. Deposition of sediment from up-slope occurred in areas of standing water. Flow was not always down the slope of the plot but dictated by the local slope angle of the microtopographic step features. An example of the rapid accumulation of standing water is given in a series of plot photographs in Figure 5.9.

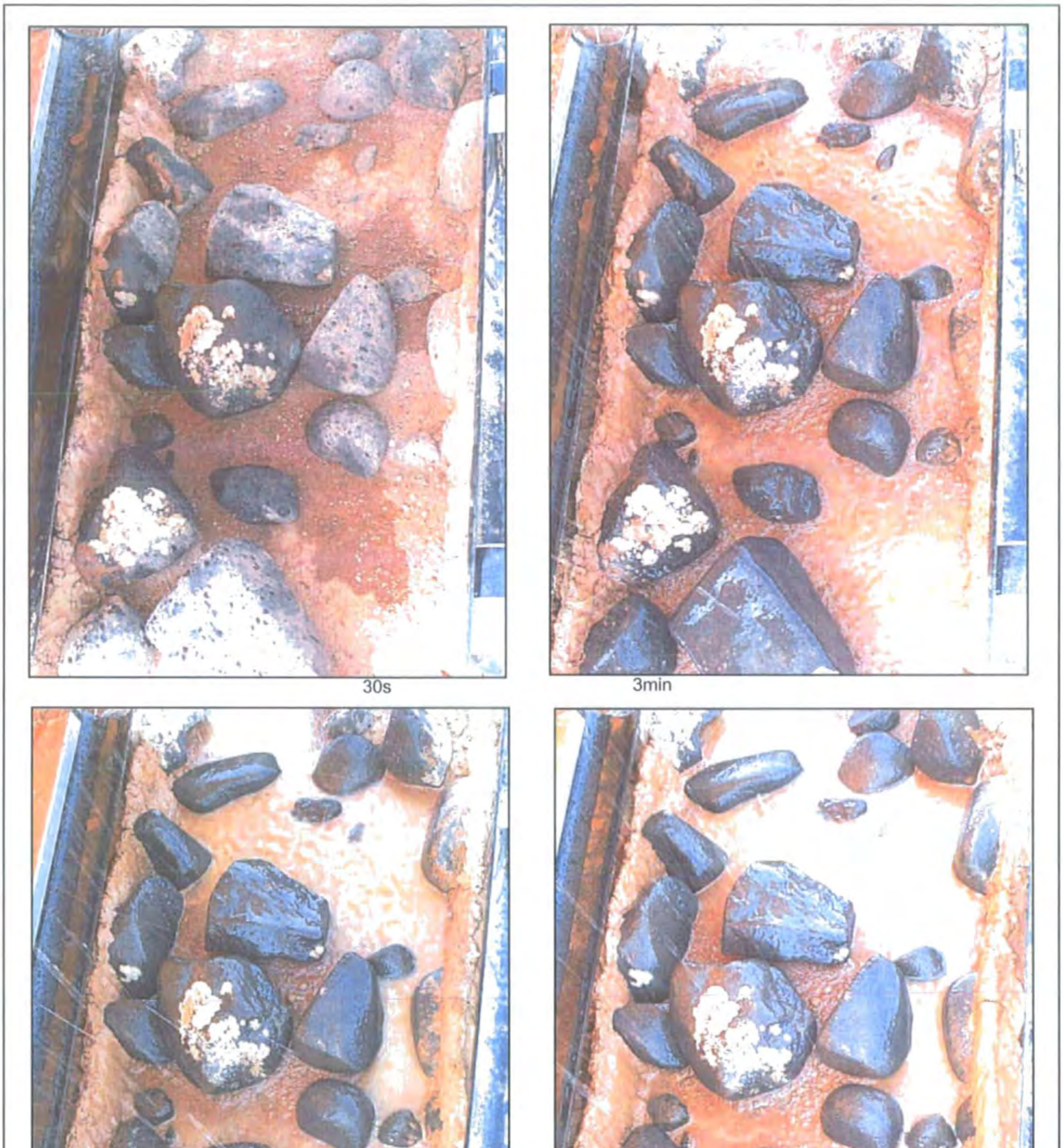


Figure 5.9 Standing water accumulation (trial experiment)

When rainfall application was halted runoff quickly ceased. Significant evaporation but limited infiltration left standing surface water for up to two and a half hours after the experiment, though this time varied. The removal of clasts from the surface after the experiment revealed the pattern of infiltration into the surface. Wetted perimeters were excavated and mapped after each experiment. Infiltration focused around the perimeters of clasts but the covered sediment directly beneath the clasts was often found to be dry. Previously desiccated areas with cracked crust surfaces showed the greatest wetting depths (mean depth = 0.06 m). Areas where standing water had been present showed very sharp wetting fronts. A steeper gradient in the wetting front was found at the perimeter of partly submerged clasts. Where the clast stood proud of the surface the boundary of subsurface wetting was less sharply defined. In areas where a crust or desiccated crust was present, the wetted perimeter was found to be highly irregular, whereas where the surface was dominated by unconsolidated fines the wetting front was commonly more regular. Wetted perimeter emerges at the surface beneath part submerged clast, such that the central area of covered sediment commonly remained dry. Wetted depths increased down-plot slightly in areas devoid of clasts; at the plot lip, mean depth = 0.12 m, 0.5 m up-slope mean depth = 0.095 m. Several notable patterns in the depths and nature of sediment wetting was linked to the presence of surface clasts (Figure 5.10).

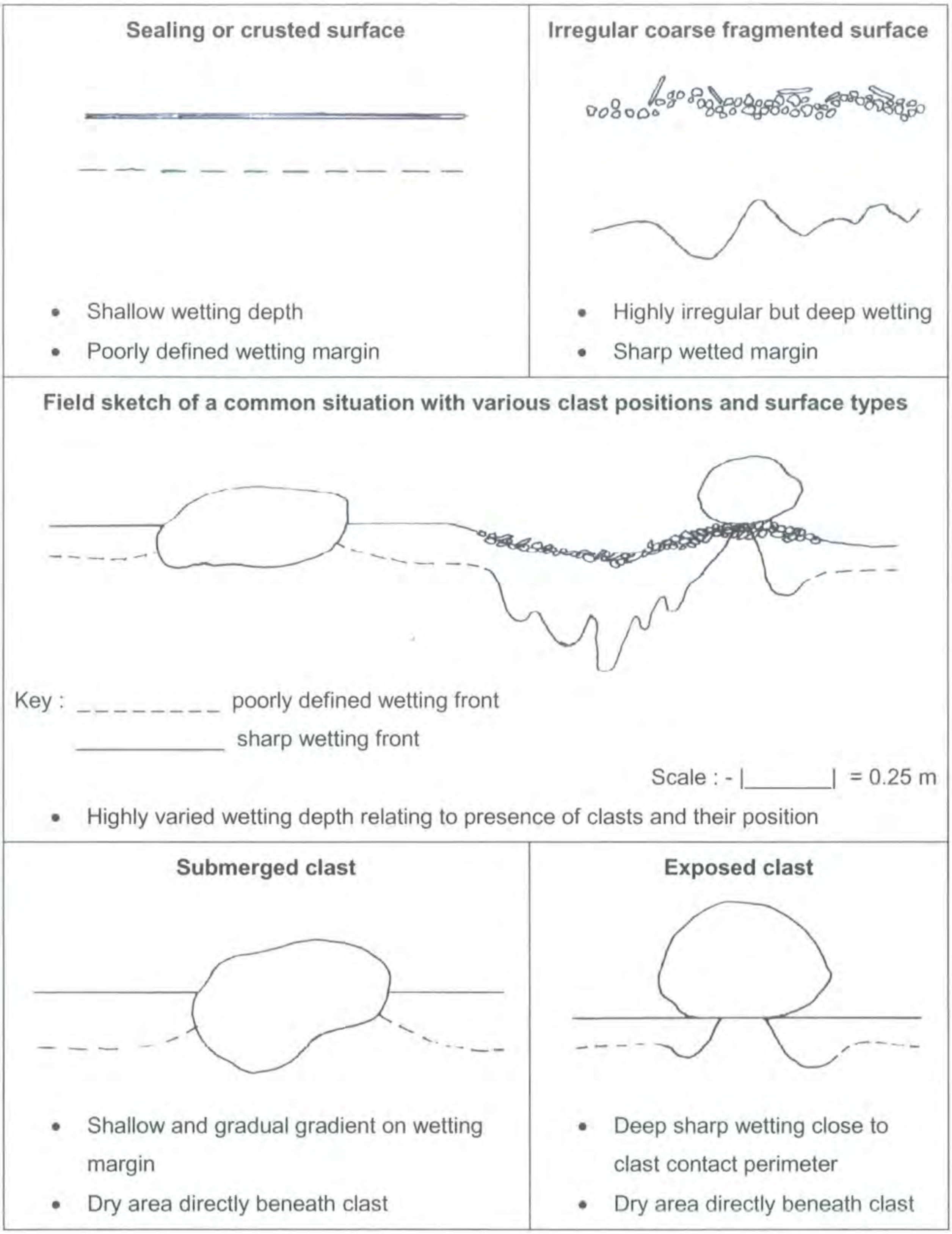


Figure 5.10 Diagrams of various wetting perimeters

5.5.2 General quantitative observations

Variability in surface response is reflected in the diverse nature of infiltration, runoff generation, maximum and timings between plots. The relationship between mean runoff and applied rainfall for all 27 experiments shows the degree of dispersion in runoff generated from the plots but the mean runoff generated from all 27 plots shows a logical variation with the applied rainfall intensities (Figure 5.11). Summary statistics from all 27 experimental plots are detailed in Table 5.2.

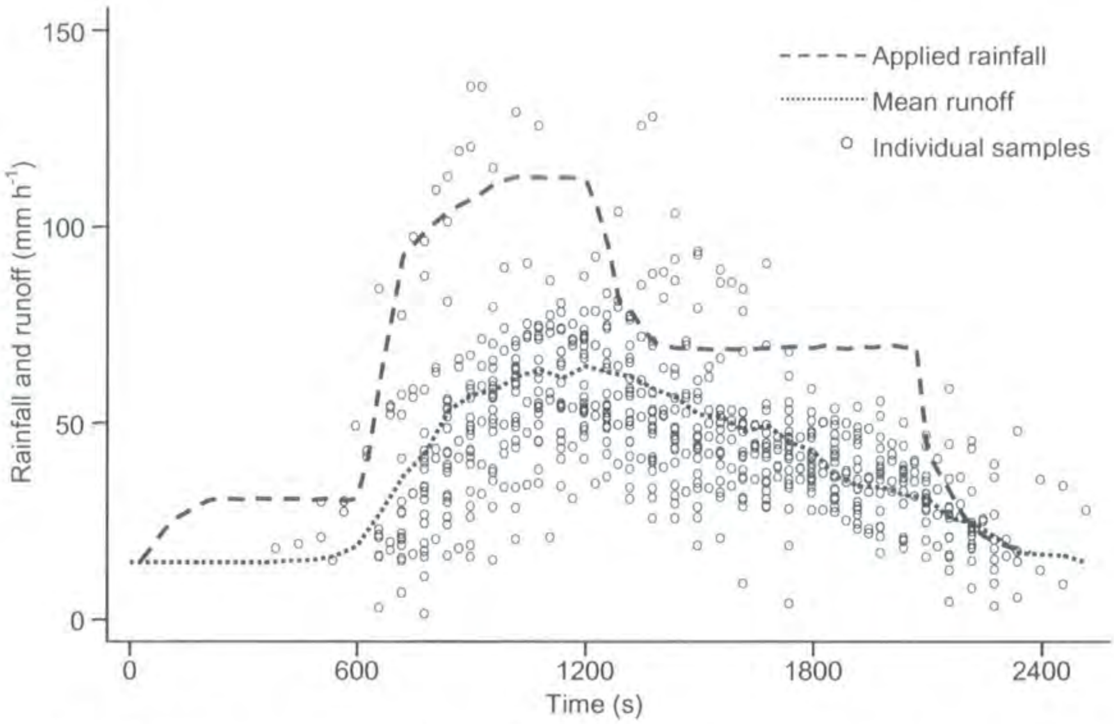


Figure 5.11 Mean runoff, applied rainfall and all individual samples taken at all 27 plots

Runoff occurred after a mean time of 683 s after the onset of the experiment, 83 s after the peak applied rainfall intensity. With a lag of approximately 390 s for the rainfall simulator output to increase from 17.5 to 100 mm h^{-1}, this represents a very rapid surface response to a change in applied rainfall intensity. An intensity of 17.5 mm h^{-1} was found to generate runoff after a mean time of 1080 s during trial experiments, again demonstrating the rapid response of the surfaces. The minimum time to runoff generation occurred at 390 s with the maximum after 930 s (Table 5.2). Times to maximum runoff varied accordingly. Mean peak discharge, recorded as 66.9 mm h^{-1}, was achieved after 1151 s, with the minimum time-to-peak discharge occurring at 660 s and the maximum time to peak runoff occurring after 1500 s. The maximum recorded runoff was 132 mm h^{-1} and the minimum value was 28.6 mm h^{-1}. Mean peak discharge is obtained 300 s after the cessation of peak rainfall intensity. The lag time to mean peak discharge reflects the increasing connection between areas of the plot as the volumes of standing water accumulated. If maximum discharge is not achieved during the period of maximum intensity, it is likely to be delayed by the reduced rainfall intensity in the latter stages of the experiment.

Experiments in the northeastern Badia show that temporal variations in infiltration and runoff generation vary greatly between plots. Some of the experimental plots show highly responsive surface hydrology which closely reflects the rate of applied rainfall. The correlation between applied rainfall and generated runoff varied greatly between plots. A more muted response, showing both extensive lags and a poor correlation between rates of runoff and rainfall application, were noted to generally occur towards the toe of the slope profile. Deviation about the mean runoff increases with rainfall intensity. A lag-time is evident between the onset of peak intensity and peak discharge. Runoff tails off rapidly after the end of simulated rainfall. The rising limb of the hydrograph is more clearly defined and abrupt than the falling limb, indicating the responsive nature of the surface. Falling limbs are more sporadic and showed a greater level of variability in runoff.

Plot position	Plot number	Maximum runoff rate (mm h^{-1})	Mean runoff rate (mm h^{-1})	Runoff standard deviation	Total runoff (mm)	Mean sediment yield (g mm^{-1} h^{-1})	Total sediment yield (g)	Sediment yield standard deviation	Maximum sediment yield (g)	Time to runoff initiation (s)	Time to maximum runoff (s)
STT	1	80.400	42.249	21.389	4929	0.059	1.653	0.059	0.213	11.590	1140
STT	2	66.000	41.249	14.890	3953	0.009	0.212	0.014	0.070	11.300	1080
STT	3	74.640	41.983	18.692	5073	0.223	6.468	0.427	1.496	11.220	1080
STM	1	40.800	31.469	9.331	3278	0.015	0.347	0.046	0.231	14.000	1140
STM	2	54.960	37.173	12.211	4182	0.124	0.335	0.040	0.207	12.130	1140
STM	3	53.760	27.500	10.055	2750	0.006	0.143	0.008	0.029	12.470	1200
STB	1	54.480	27.844	14.839	2996	0.044	0.845	0.102	0.458	11.070	1140
STB	2	28.560	18.400	8.321	2070	0.226	6.113	0.230	1.218	12.400	1350
STB	3	41.280	18.691	12.424	1947	0.048	1.205	0.074	0.312	13.010	1260
CCT	1	69.360	31.324	18.316	3785	0.019	0.558	0.040	0.201	9.180	1200
CCT	2	76.800	40.270	21.307	4027	0.016	0.391	0.044	0.201	15.300	1350
CCT	3	86.160	40.648	26.150	5081	0.047	1.421	0.048	0.131	13.090	1500
CCM	1	46.800	28.720	12.556	3590	0.045	1.347	0.061	0.262	11.300	1350
CCM	2	69.120	36.665	18.479	3972	0.016	0.417	0.436	0.204	12.000	1140
CCM	3	48.960	39.777	12.362	2554	0.084	1.854	0.109	0.581	11.450	1020
CCB	1	54.000	33.757	12.862	4155	0.055	1.751	0.060	0.232	10.110	1020
CCB	2	56.400	29.956	14.930	2746	0.123	2.708	0.089	0.369	10.470	1200
CCB	3	65.520	41.639	16.669	4870	0.041	1.116	0.060	0.264	8.390	1110
CVT	1	75.600	35.881	16.970	4173	0.013	0.403	0.020	0.213	9.110	660
CVT	2	55.200	28.412	13.923	3486	0.050	0.506	0.076	0.213	12.010	1140
CVT	3	103.200	39.545	20.568	3876	0.012	1.105	0.023	0.422	6.300	810
CVM	1	136.000	87.778	25.798	9399	0.153	4.064	0.108	0.181	11.300	930
CVM	2	106.800	71.647	24.504	5561	0.091	1.579	0.107	0.405	12.000	840
CVM	3	72.480	54.707	19.626	4321	0.053	1.043	0.012	0.359	12.000	1290
CVB	1	53.760	27.880	15.005	2091	0.014	0.244	0.012	0.258	11.300	1410
CVB	2	48.000	34.320	9.862	3432	0.025	0.584	0.056	0.201	11.000	1320
CVB	3	65.520	44.271	14.182	4796	0.012	0.299	0.025	0.205	10.560	1260
Mean		**66.095**	**38.287**	**16.156**	**3966**	**0.060**	**1.434**	**0.088**	**0.338**	**11.336**	**1151**

Table 5.2 Plot experiments, summary statistics

5.5.3 Rainfall partitioning and infiltration

Aggregated results from all experiments return a mean runoff coefficient of 0.223, equivalent to 13.3 mm h^{-1} runoff under this storm hydrograph, indicating a mean steady state infiltration rate of 46.1 mm h^{-1}. Surface water storage was estimated immediately after 10 of the 27 experiments. Standing water depths were also measured. Standing water was commonly observed to accumulate over 75% of the exposed sediment areas. Standing water reached a maximum depth of 27 mm, with a mean value of 13 mm. Aggregated over the mean percentage of exposed sediment cover (52.9% of plot area for all 27 plots) this represents 19.7% of the applied rainfall volume. Infiltration, taking account of surface storage, therefore represents 58% of applied rainfall, with a mean value of 36.2 mm h^{-1}. Infiltration varies considerably between locations, but corresponds well with previous studies in the region. For example, Warburton (1998) suggested a mean infiltration rate of 24 mm h^{-1} for the Badia side slopes. The higher rate obtained here is attributed to the presence of clasts. The experiments undertaken by Warburton (1998) only considered interclast sediment areas.

Based on the calculations outlined above, rainfall partitioning from all 27 experimental plots can be disaggregated as follows. Surface storage accounts for 19.7%, infiltration 58.0% and runoff 22.3% of rainfall. Plot leakage is estimated at less than 5% of applied rainfall, which was lost both though lateral leakage of surface storage, loss at the plot lip and lateral infiltration beneath the plot boundaries.

Observation of infiltration processes from the rainfall simulation is complicated by the coalescence of ponded areas, often represented by an oscillation of runoff about a mean steady value. Runoff can therefore only be considered as quasi-stable (Holden, 2000), whereas infiltration rates maybe stable or steady. Runoff as a surrogate for infiltration is therefore not reliable on this type of surface with this plot size, but nonetheless provides some interesting results. A series of twin-ring infiltration experiments was undertaken to give a better estimation of water exchange at the surface. The use of infiltration rings allows the calculation of steady state and maximum infiltration rates and is not subject to the complexities of variable rainfall intensity in storm simulation. Three twin-ring infiltration experiments were conducted in parallel at each of the nine slope positions to gain a statistically robust sample. The data generated are averaged at each location, and Hortonian type infiltration regression curves fitted (Equation 5.1).

(Eq. 5.1)

$$f = f_c + (f_o - f_c)e^{-kt}$$

where : f = infiltration capacity
f_c = final infiltration rate (asymptote)
f_o = the initial infiltration
k = a constant

The Hortonian equation is fitted by a non-linear least squares method which seeks to minimize the sum of squared deviations between the predicted and observed infiltration rates. The application of a Hortonian-type equation is not without its limitations but is preferred over the alternatives. The Hortonian type equation is favored above the Philip equation, as the latter is seen only to be applicable after whole surface ponding, which in this instance only occurs in the latter stages of the experiment. As Slattery (1994) notes, there are difficulties in applying the theoretical infiltration curve derived by Philip (1957). The Hortonian model initially assumes infinite infiltration, until the rate equals the rainfall intensity. After this point the infiltration curve dictates how much of the water enters the surface and how much is diverted to overland flow. By their nature both the Philip and Hortonian infiltration curves are forced though initial and final infiltration levels. Given the relatively sporadic nature of infiltration calculations generated from the rainfall simulation, this type of model is better suited to the more stable results generated by the ring infiltration experiments.

An example of the Hortonian type infiltration curves are given in Figure 5.13. This demonstrates the speed at which the infiltration rate stabilizes to a steady state. The final mean infiltration value of 36.2 mm h^{-1}, derived from the rainfall simulation, is also shown in Figure 5.12.

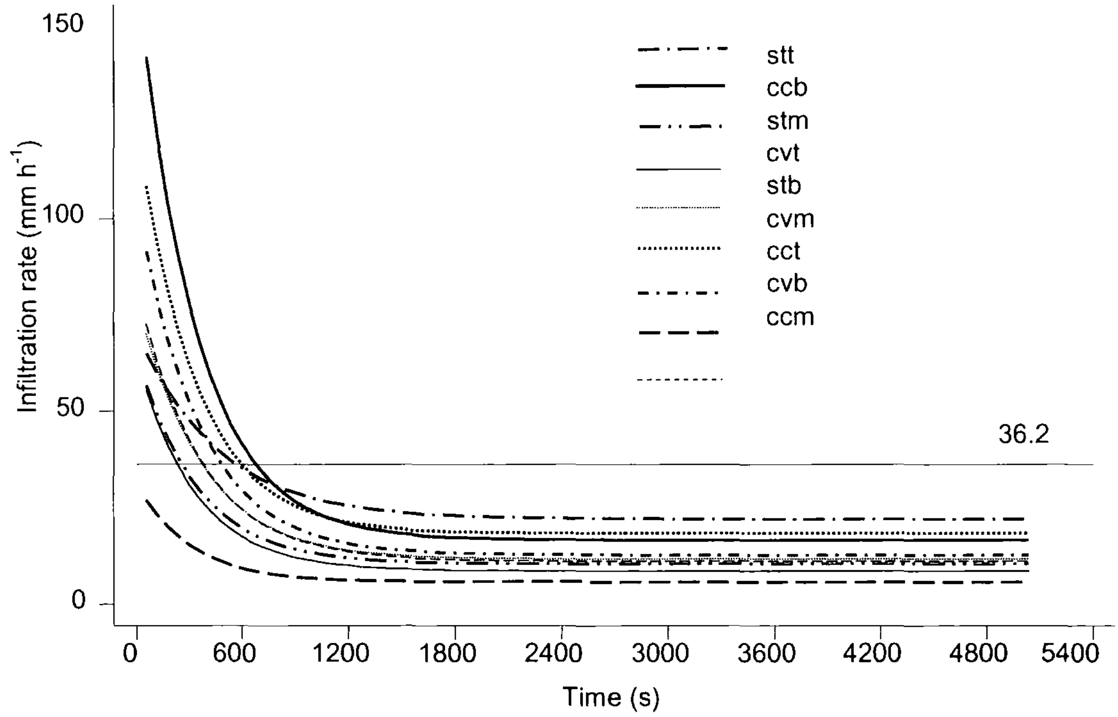


Figure 5.12 Hortonian infiltration regression curves at the 9 experimental sites. Mean infiltration curves have been derived from the three experiments at each plot position.

Results from the ring infiltration experiments show a difference to those results generated from the rainfall simulation. Mean steady state infiltration values gained from the ring infiltration suggest a rate of 13 mm h^{-1}, as opposed to a value of 36.2 mm h^{-1} derived from the rainfall simulation. The difference in infiltration rates obtained is attributed to differences in experimental procedure. The rainfall simulation experiments encompass a relatively large plot area (0.5 m^2), which includes both boulder and exposed sediments. The ring infiltration experiments where undertaken over a small spatial area (0.02 m^2) which is not sufficient to include basalt fragments or clasts. The relative shape of the circular infiltration plot and the rectangular rainfall simulation plot also means that edge effects relative to the surface area are greater in the rainfall simulation experiments than the infiltration. Given the low levels of lateral seepage of water from the rainfall simulation plots, the difference in infiltration rates seen from the rainfall simulation is attributed to the presence and variable nature of boulders within the experimental area. The presence and nature of surface clasts is a key control on slope hydrology. A small degree of variability may be attributable to the infiltration characteristics of the sediments at the various locations. For example, Hortonian infiltration regression curves for the top, middle and bottom plot locations, (Figure 5.13), show a decrease in infiltration capacity down-slope.

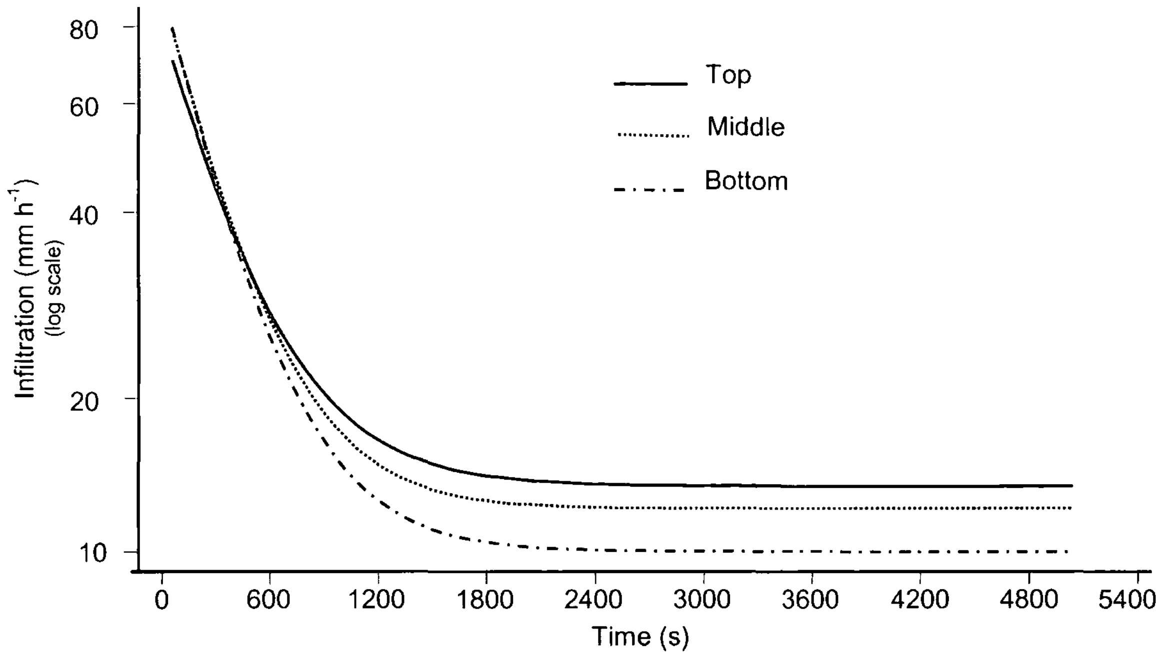


Figure 5.13 Hortonian infiltration regression curves, grouped by plot position

Steady state infiltration and runoff relative to applied rainfall was observed to occur rapidly after the start of the experiment at some plot positions. The abundance of standing water suggests a limited infiltration capacity, which in turn generates relatively large quantities of overland flow. Periods of stable runoff are characterized by a sporadic oscillation about a mean value which is here attributed to the periodic fill and burst of micro-topographic lows within the plots and the formation and development of preferential flow pathways (Plate 5.2). This type of behavior was seen to be particularly prevalent on surfaces with marked step-like micro-topography which is commonly associated with surface structures. The oscillations therefore are frequently not a reflection of the variable nature of the infiltration but rather a complication of the rainfall simulation technique.

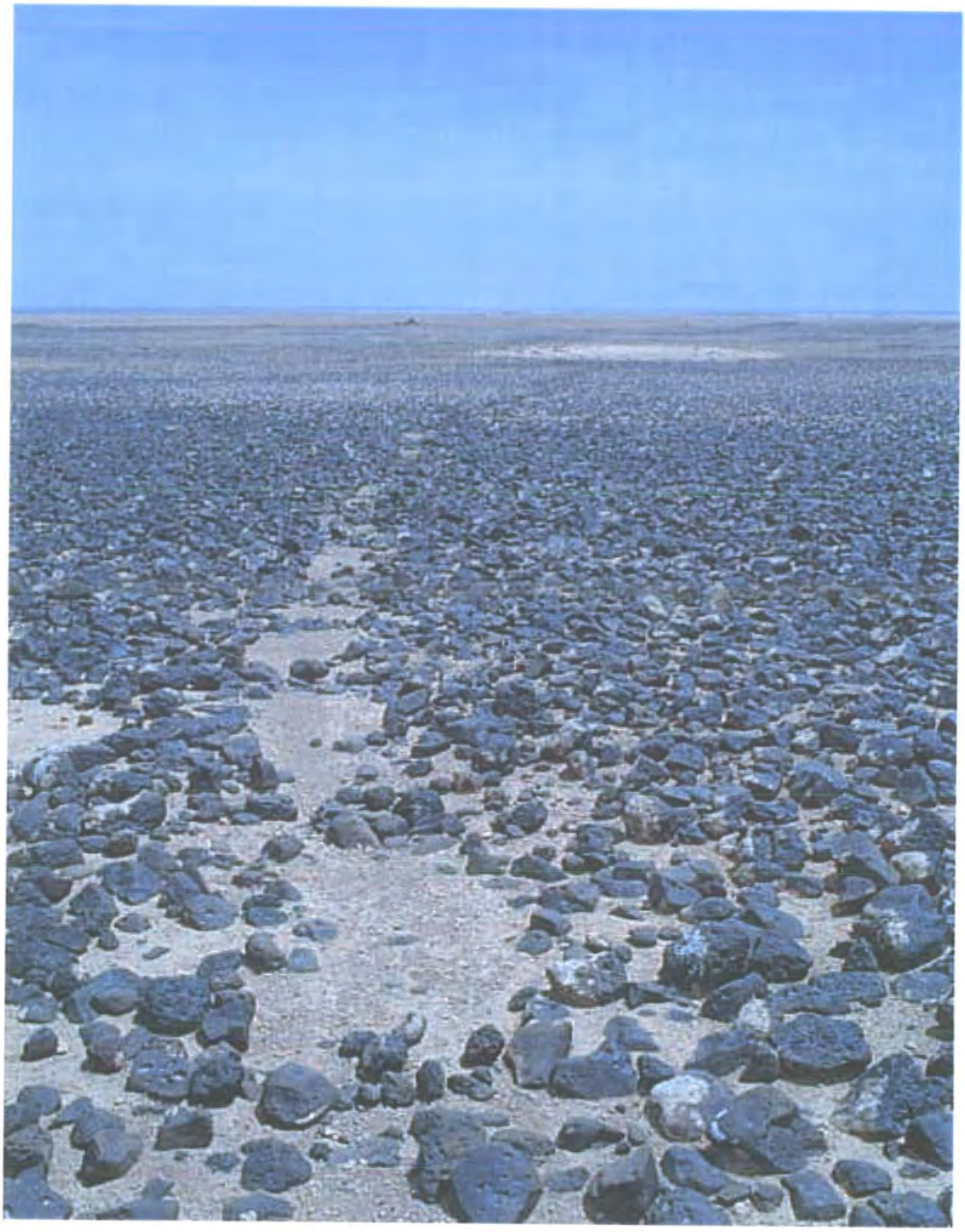


Plate 5.2 Preferential flow pathways, Qa'a Al Buqei'wiya

5.5.4 Sediment transfer

Sediment yields from the experimental plots were generally low with several of the runoff samples retaining so little sediment that the accuracy of the balance measurement was less than the sediment mass. In these instance sediment mass was assumed to be zero. The mean sediment yield for all 27 experiments was 1.43 g, with a maximum of 6.47 g and a minimum of 0.14 g. As with runoff generation, sediment yields were seen to fluctuate throughout the period of the experiment but again appear to oscillate around a constrained mean value. Peak sediment yields occurred after a mean time of 900 s from the beginning of the experiments which corresponds closely with the onset of peak rainfall intensity though a high standard deviation of time to sediment maximums shows the sporadic nature of sediment dynamics. A statistically strong link between mean runoff and mean sediment yield (r^2 = 0.707, α = 0.01) and more significantly rainfall intensity and mean sediment yield was found (Figure 5.14).

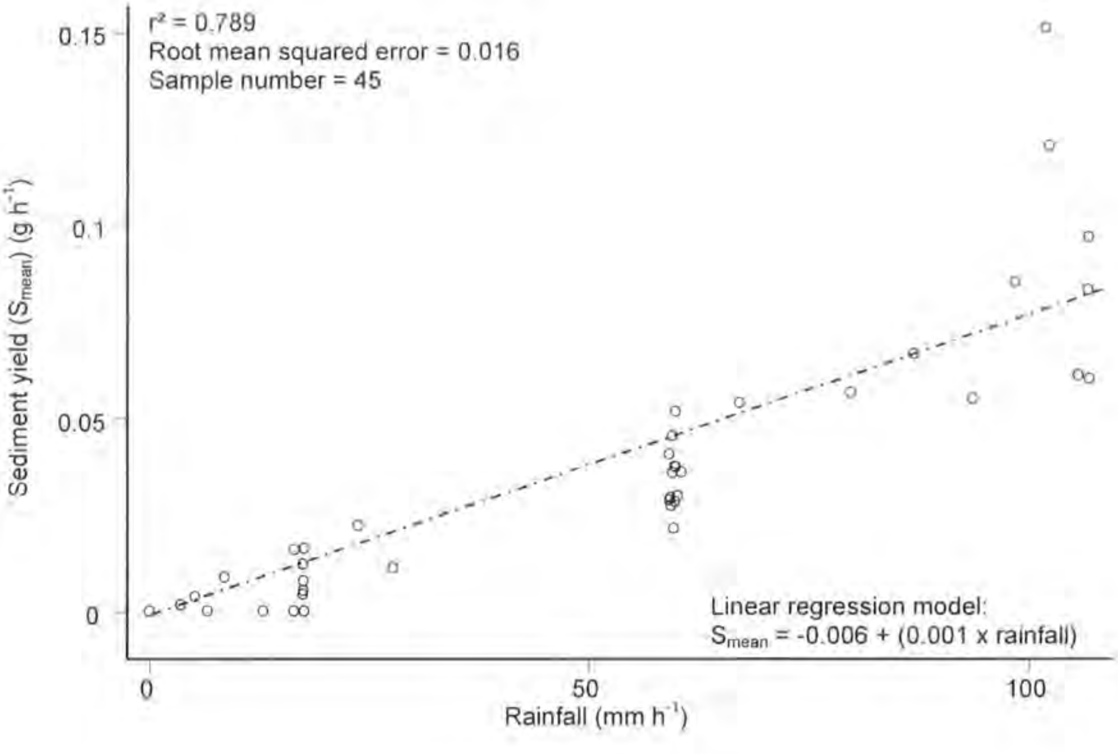


Figure 5.14 Relationship between rainfall intensity and mean sediment yield

Sediment yield is controlled more directly by raindrop and splash detachment rather than entrainment by overland flow, under these experimental conditions, though both are significant factors. This suggestion is perhaps not surprising in a plot of 0.5 m^2, where overland flow is limited. The importance of the relationship between rainfall intensity may be reduced under natural conditions if ponding depths and up-slope area increase. Raindrop impact absorption and the velocity of overland flow under natural conditions maybe more important controls on surface sediment dynamics (Cerda, 1998). It is also interesting to note the increase in mean sediment yield variability with intensity. Higher intensities tend to exaggerate differences in surface response between sites. The diversity in surface response is attributed to the variable protection afforded to the surface by the clast cover.

The generally low levels of sediment removal from the plots can be attributed to several factors. The plot area in itself is relatively small and the surface sediments are commonly crusted and rapidly seal after the onset of rainfall. The high frequency of low magnitude events which are not sufficient to instigate overland flow, may act to increase surface sealing, increasing this effect. Runoff on a plot of 0.5 m^2 will never obtain significant magnitude. Where concentrated overland flow does occur the volume of water is therefore relatively small. Scour or rill development will be limited and hydraulic deformation of the sediment bed is transport muted.

5.5.5 Heterogeneity in surface hydrology

Heterogeneity in surface hydrology is a commonly cited phenomenon in semi-arid environments (Agnew and Andersen, 1992; Sharma *et al.,* 1980). The results show coherent levels of heterogeneity between plot locations but significant variation between contiguous plots is still apparent. The diversity in surface response is attributed to both variations in sediment character and ground surface clast cover, though this effect has been minimized by using the image analysis based plot location method. Heterogeneity in surface response can be linked to slope position.

Plot location	Mean runoff σ (mm h^{-1})	Max runoff σ (mm h^{-1})
Top	19.02	28.74
Middle	14.59	21.60
Bottom	10.23	19.12

Table 5.3 Standard deviation in hydrological response as influenced by slope position

Table 5.3 shows standard deviation of hydrology statistics grouped by plot location. It suggests that slope position influences not only magnitude of runoff generation, but also the nature of variability of surface response. Surface hydrology, as represented here by mean runoff and maximum runoff appears to be more consistent between plot locations towards the base of the slope profile.

An interesting and important question is raised as to whether this pattern is cause or effect of slope hydrology? Surface form at the base of the slope profile may be modified by slope process such that the response is more muted and less variable. For example, increased volumes of runoff from the up-slope area increase attrition and the removal of clasts from the slope toe. This process increases the area of exposed sediments for infiltration, hence reducing volumes of runoff. Potential feedback mechanisms suggest that the interrelationships between the controls of surface forms may vary between locations and may be indicative of a homeostasis between form and process action.

Several distinctive trends in surface hydrology have been established by examining generalized results from the rainfall and infiltration experiments. The results have identified that around the mean trends of surface hydrology there is a significant degree of variability between disparate plots. The image analysis of the surface characteristics has identified an equally diverse ground configuration, as dictated by the presence and nature of surface clasts.

5.6 Slope profile hydrology

Rock fragments often a contradictory effect on overland flow production and surface hydrology (Poesen, 1994). The following section describes an examination of the influence of ground surface cover and slope variables in the context of the two-dimensional slope profile. The systematic, down-slope changes in ground surface cover have previously been linked to what is suggested to be slope dominated process action.

From a comparison of the experiments undertaken in this study it is clear that the presence of surface clasts has a profound influence on surface hydrology. Rainfall simulation and ring-infiltration experiments to examine the infiltration characteristics of the surfaces return very different results for identical locations. The difference between the experimental procedures is the inclusion of boulders within the area under examination. The variation in surface hydrology is not purely a function of variability in sediments between locations but is influenced by the presence and configuration of surface clasts. Rainfall simulation repeatedly shows greater levels of variability between contiguous and disparate locations, whereas more consistent results were obtained from the ring-infiltration experiments. It is suggested that presence of surface clasts greatly influences the nature of surface hydrology, in a systematic manner.

Aggregated statistics whereby mean values are taken across all three experimental slopes yield poor correlations between ground cover measures, hydrological measures and sediment dynamics. For example mean runoff (R_{mean}) correlates with percentage clast cover (Gcp) with an r^2 value of 0.0006 for all 27 plot locations. As was seen with the image analysis results, more success is found when the data are grouped either into whole slopes or plot positions. Results generated from image analysis on the area rainfall simulation plot are also used to examine whether a more detailed description of the surface at the plot scale provides a better understanding of plot hydrology. These are compared to results generated form the larger image analysis plot.

5.6.1 Straight profile

The straight profile site provides a good example to test the relationship between ground cover and hydrology without the added complication of a concave or convex slope profile form. Changes in ground surface cover are now well understood at this site. Additionally, the long length (204.7 m) of the profile may exaggerate absolute differences in form and process due to slope controls. Regression analysis between slope controlled variables, ground cover of both the rainfall simulation plots and the image analysis plots and slope hydrology returns significant least squares correlations (Table 5.4).

Table 5.4 shows several statistically significant relationships between slope hydrology, slope and ground cover. The majority of significant correlations relate measures of runoff to the controlling variables, in Table 5.4 enclosed within the box. First, consistently significant relationships are found between runoff and not sediment load. As previously seen when considering the generalized statistics for all experiments (5.5.2), there is little relationship between sediment yield, runoff or slope controls. Instead sediment yield is strongly linked to applied rainfall intensity, suggesting the importance of splash detachment. The low sediment yield is related to limited levels of runoff and hydraulic deformation, as dictated by plot size. On the straight slope example, with there is no clear correlation apparent between sediment yield variables and ground surface or slope variables.

The second observation from these results is the poor relationship between the whole plot derived statistics (Gcp_{plot}, $EdgeTot_{plot}$, B_{plot}) and the hydrology of that plot. Much greater significance is achieved in comparisons between the image analysis derived statistics

(Gcp, $EdgeTot_{im}$, CVB_{im}, B_{im}) from the image analysis plot, a plot an order of magnitude greater in area. This has several implications. Results generated from a small plot, derived using the same image analysis methodology, do not correlate well with surface hydrology. Poor correlations between surface cover character and surface hydrology maybe explained as an inadequacy of sampling. The sample size maybe statistically significant in terms of understanding particle size distribution, but in not of sufficient extent to understand surface hydrology. Sample size and spatial extent is therefore of paramount importance for studies which aim to use measures of surface character to understand surface hydrology on these surfaces.

	Variable	Runoff R_{max}	Runoff R_{mean}	Runoff R_{Tot}	Sediment S_{max}	Sediment S_{mean}	Sediment S_{Tot}	Timings TR_{Start}	Timings TR_{max}
Plot statistics	Gcp_{plot}	0.039	0.019	0.006	0.026	0.000	0.041	0.087	0.015
	$EdgeTot_{plot}$	0.008	0.006	0.010	0.199	0.353	0.200	0.137	0.048
	B_{plot}	0.000	0.031	0.026	0.123	0.113	0.134	0.068	0.001
Slope	PltAngle	0.547	*0.797*	*0.690*	0.032	0.016	0.015	0.035	0.544
	UpslpAngle	0.580	0.430	0.435	0.073	0.032	0.119	0.427	0.228
	PltDist	*0.695*	0.852	*0.765*	0.003	0.002	0.000	0.127	0.551
	Curv	0.663	0.555	0.544	0.019	0.084	0.045	0.386	0.310
Image analysis ground cover statistics	Gcp	*0.731*	0.698	0.663	0.017	0.007	0.044	0.313	0.413
	EdgeTot	*0.681*	0.588	0.572	0.039	0.016	0.075	0.372	0.333
	CVB	*0.744*	0.745	*0.699*	0.010	0.004	0.031	0.280	0.448
	B	0.281	0.113	0.136	0.157	0.070	0.208	0.443	0.041
	VolwMb	*0.732*	0.700	0.664	0.017	0.007	0.043	0.312	0.414
	AreawMb	*0.710*	0.645	0.620	0.027	0.011	0.059	0.344	0.374
	EdgewMb	0.661	0.552	0.542	0.046	0.020	0.085	0.387	0.085
Spatial	Fractal	*0.738*	**0.829**	*0.758*	0.000	0.007	0.000	0.191	0.521
	Theissen	*0.717*	**0.847**	*0.767*	0.001	0.001	0.002	0.153	0.002

Significance values : $\alpha = 0.05$ – *italics*; $\alpha = 0.01$ – **bold**

Variable name	Variable type	Description
Gcp_{plot}	Plot variables	Percentage clast ground cover – rainfall simulation plot (%)
$EdgeTot_{plot}$		Total edge length (m)
B_{plot}		Mean intermediate axis (m)
PltAngle	Slope variables	Rainfall simulation plot angle (degrees)
UpslpAngle		Mean angle of slope 10 m above plot (degrees)
PltDist		Distance of plot from slope crest (m)
Curv		Slope curvature (and of the slope 10 m above the plot, minus the angle of the slope 10 m below the plot)
Gcp	Image analysis ground cover variables	Percentage clast ground cover – image analysis plot (%)
EdgeTot		Total edge length – image analysis plot (m)
CVB		Coefficient of variation
B		Mean intermediate length (m)
VolwMb		Volume weighted mean intermediate axis length (m)
AreawMb		Area weighted mean intermediate axis length (m)
EdgewMb		Edge length weighted mean intermediate axis length (m)
Fractal	Spatial variables	Box fractal dimension for sediment area
Theissen		Standard deviation of number of vertices of Theissen polygon network

Table 5.4 Correlation statistics – straight profile

Of the relationships described (Table 5.4), the diversity of significant variables is notable. Slope, ground surface cover and spatial measures of the surface form all return statistically significant values of r^2. The surfaces therefore present a complex system whereby many factors appear to influence hydrology, though collinearity between variables is inevitably apparent. Delimiting one variable from another appears difficult given that the relationship and relative importance of variables changes between locations. There is the role of surface form influencing process and process influencing surface form. Differentiating geomorphological cause from effect in such a system where variables are interdependent is difficult to achieve using field experiments such as this. The rainfall simulation is designed to assess surface hydrology. The adjustment of the surfaces through the movement of clasts or the reworking of the clast population though weathering and erosion requires either a much greater magnitude of runoff, which may be obtainable in a whole slope sheet flood, or a much longer time-frame, whereby the movement process of clasts is iterative. The study of surface hydrology appears to be an adequate measure of surface process variability, given the significant relationships between slope form ground cover and plot hydrology variables.

The results presented for the straight slope profile compliment the suggestions made by Dunkerley (1994). Dunkerley advocated the importance of considering appropriate statistics that could be conceptually related to process action. Table 5.4 details the correlations between slope hydrology and weighted means, as suggested by Dunkerley (1994). $VolwMb_{im}$, $AreawMb_{im}$ and $EdgewMb_{im}$ show statistically significant relationships with runoff variables ($\alpha = 0.05$). It is also interesting to note the increasing strength of the correlations presented as the weighted mean approaches a volume approximation of clast form ($VolwMb_{im}$). Edge length weighting ($EdgewMb_{im}$) and area weighting ($AreawMb_{im}$) remain significant, but less so than $VolwMb_{im}$. This suggests the importance of both edge length, previously suggested as a transition zone for water infiltration (Poesen and Ingelmo-Sanchez, 1992), clast area, which affords protection from raindrop impact (Poesen and Lavee, 1994), and clast volume.

The relationship between clast volumes, despite being the most significant here, is less clear. It is suggested that this acts as a surrogate for both edge length, area and as a hydraulic roughness element which acts to impede and channel flow. All of the weighted means behave more significantly than the commonly cited crude mean intermediate axis (B_{im}), again advocating the importance of appropriate statistics. It is also interesting to note that actual equivalent measures which Dunkerley's (1995) weighted means aim to approximate, perform better than statistical approximations. For example $EdgewMb_{im}$ r^2 = 0.66, whereas the image analysis derived $EdgeTot_{im}$ r^2 = 0.68. It is reassuring that commonly employed percentage cover (Gcp) performs well, returning consistently high levels of significance. Additionally, the degree of clast sorting, here represented by CVB_{im}, is significant as a control on runoff. The implication of the results is that simplistic measures of ground surface cover may not always be appropriate. Cover percentage, weighted mean clast sizes and clast sorting all appear to be significant influences on runoff generation and magnitude.

A further additional set of ground cover variables are the spatial statistics. In this example Theissen polygon analysis (Theissen) and fractal dimension results return the second and third highest degrees of significance as a control on R_{mean}, R_{max} and R_{Tot}. It is interesting to note here that although the experimental plot size chosen does not encompass an area of spatial extent large enough to be considered homogenous, the hydrological response still reflects the organizational structure of the surface. A consideration of the spatial extent of the ground surface clast distribution is therefore important in this instance. The difficulty with extrapolating from the analysis is the consideration as whether the spatial variables are a cause or effect of surface hydrology. It has been suggested that ground clast structures can act as dams to impede runoff, particularly where polygonal networks of clasts are present. Tightly locked clast structures will reduce the flow velocity and sediment transport capacity, potentially encouraging infiltration, and further modification of the clast surface. If a locking structure acts as a dam to flow, than it is likely that the constriction to flow will be breached when the surface water overtops the clasts. This may encourage scour erosion, and direct the flow into the sediment bed. Under a mechanism such as this, does an organized surface self perpetuate its character by impeding flow, reducing runoff and increasing infiltration? Is then a feature such as surface structure a property of the surface that cannot be logically linked to the other variables considered, or is it acting as a surrogate for another process? The link between surface pattern and runoff is therefore an important consideration.

The most significant relationship was found between PltDist and R_{mean} (r^2 = 0.853), suggesting the importance of slope profile form on slope process. PltDist, although here presented as a site specific variable of slope, it is not a direct measure of slope at each plot. For example, plot angle (PltAngle), can be conceptually linked to process action at a point. An increased slope angle will increase runoff, as shown by the relationship between PltAngle and R_{mean} (r^2 = 0.797). PltDist is not a physical control over process in the plot, but here acts as a surrogate variable for down-slope controlled change in surface character. The variable potentially represents both cause and effect. PltDist encompasses the length of the up-slope over which runoff accumulates but also may represent the modification of the surface by increasing process action down-slope. The strength of the relationship shows that a whole slope consideration of process action at a point is vital to understanding slope hydrology in the Badia.

The results presented above indicate a highly variable surface hydrology down-slope. The interplay between cause and effect present the surface as a self-organizing surface with a degree of homeostasis acting to adjust form to process and vise versa. The variability in surface hydrology can be seen clearly by examining the mean runoff hydrographs from the rainfall simulations conducted at the three slope locations (Figure 5.15). The hydrographs indicate an increasingly muted surface hydrology down-slope, with reduced runoff maxima, increasing lag times, and reduced runoff and hence increased infiltration towards to base of the slope.

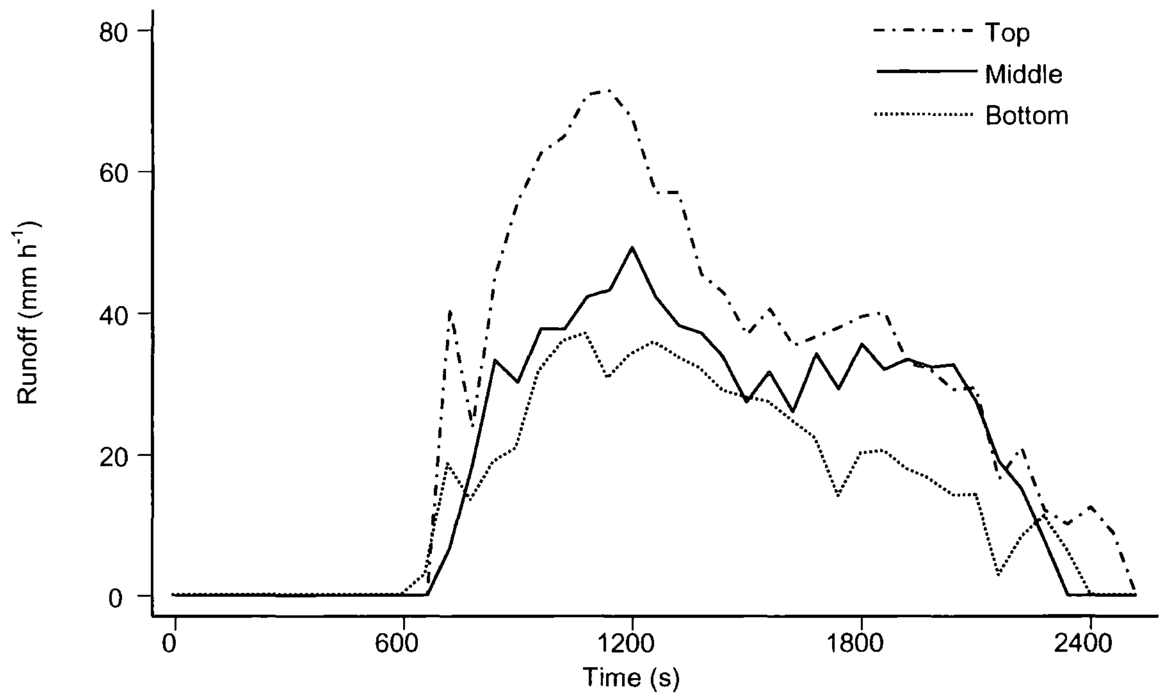


Figure 5.15 Mean runoff hydrographs for straight profile

The weak correlations between ground cover, slope and hydrology for the aggregated statistics suggests that the relationship between the variables may change their influence between sites. A method of exploring the linkages is by employing standardized results. Analysis of variables standardized to mean values for the site allow the relative change in hydrology to be assessed and conceptually linked to variations in slope form, ground cover and slope angle. Standardized results based on site mean values allow relationships to be explored at the local scale. Figure 5.16 illustrates hydrological results for the straight profile. Here mean result from the three rainfall plots at each location are standardized against the mean result for the whole slope profile. In this instance the results may appear slightly deceptive. Actual differences in morphology between plot locations on the straight profile are very small. The analysis is more beneficial on the convex and concave profiles where significant differences are apparent but data is given here for comparison. Several notable trends are apparent from this data.

First, all runoff variables appear to decrease down-slope relating well with the decrease in mean plot angle. Sediment transfer variables all vary consistently between plots. Surprisingly increased up-slope angles appear to reduce sediment yields, potentially as result of volumes of transferable sediments on the surface. If up-slope angle (here measured over the 10 m of the profile directly above the plot) are high, then flow velocities and sediment transport capacities will be high. Therefore at the middle plot location available sediments may have been removed from the plot by a previous event with a magnitude greater than at the other plot locations. Again it must be noted in this example that the actual relative differences between sites are small, so conjectures such as this should be treated with caution without further clarification. Timings appear consistent down-slope, as do the relative differences between the runoff variables.

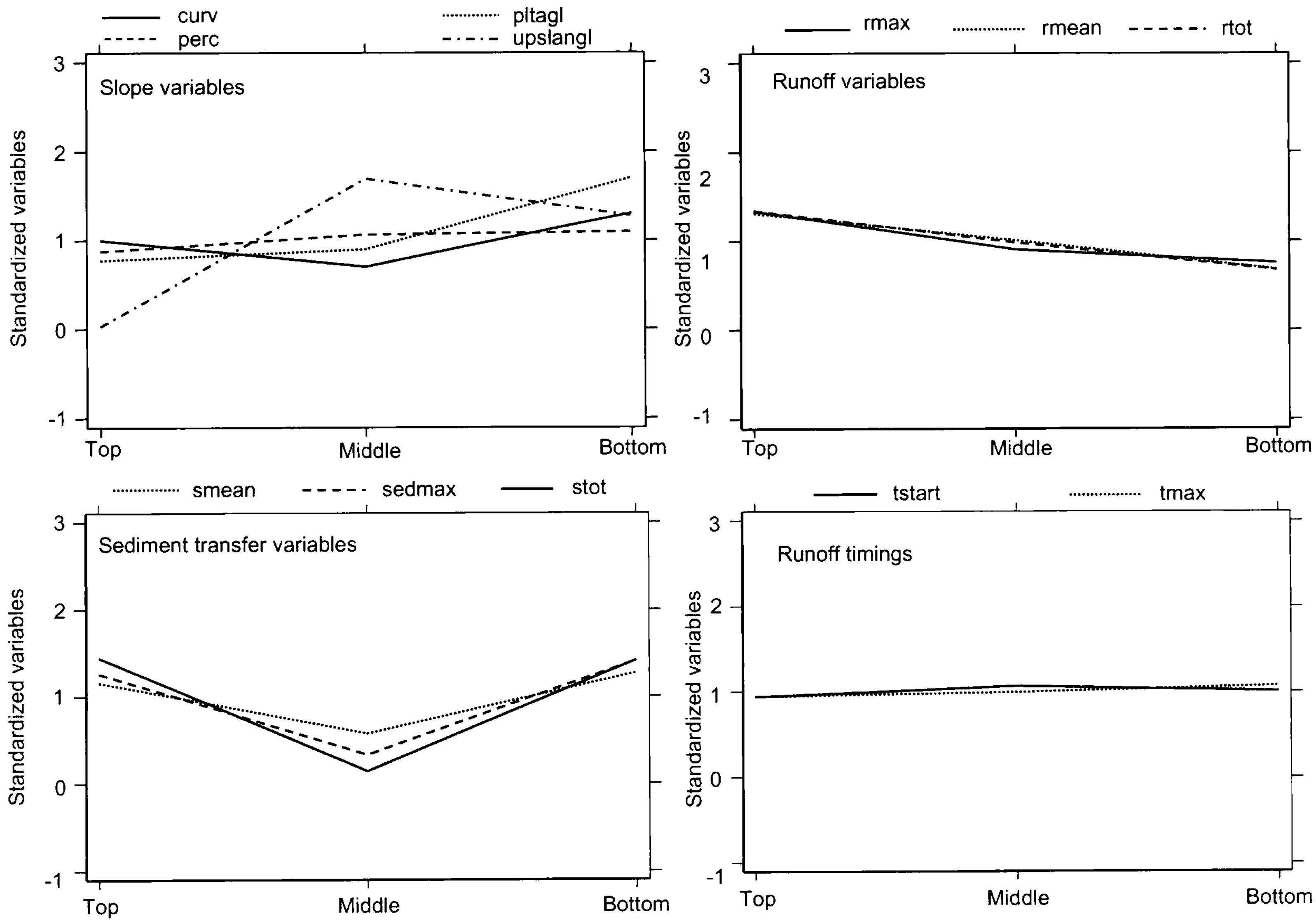


Figure 5.16 Straight slope standardized variables

5.6.2 Concave slope

Slope controlled variation in ground surface cover is more complex on the convex and concave profiles than on the straight profile surveyed in this study. It is reasonable to assume that slope hydrology is equally complex. A correlation analysis on the results from the concave profile is detailed in Table 5.5. None of the correlations return statistically significant results ($\alpha = 0.1$), but the difference in relationships is still of interest.

Regression on variables from the concave slope profile returns lower significance values than achieved on the straight profile. Significant relationships are still obtained between R_{max} and Gcp, Cvb_{im}, UpslpAngl ($\alpha = 0.1$), and the weighted mean clast intermediate diameters but none of these are strongly significant. There are no significant relationships between R_{mean}, R_{Tot} nor any of the slope or ground cover variables. Equally, sediment yields and runoff timings all fail to return significant results. The correlation analysis above explores the linearity of the relationship between variables. On the straight slope, change in ground cover character was commonly found to be linear with distance down-slope. The suggestion raised by the poor correlations on the concave example suggests that if the relationship between variables is similar to that as on the straight profile, then the nature of down-slope change is not linear. The image analysis of the ground surface cover shows similar change, which relates less well on slopes with significant departures to convexity or concavity. As has been previously shown on the straight slope example, there are significant relationships between hydrology and both ground cover and slope properties. On the concave profile, where the relationship between slope and ground cover variables is more complex, it is perhaps therefore not surprising that the pattern of down-slope variation in slope hydrology is more complex. The relationship between slope, position on slope and ground cover on slope hydrology is therefore fundamentally influenced by slope form. The importance of slope form is qualified by the consistent significance of the profile curvature variable (Curv) and up-slope angle (UpslpAngle), which returns statistically significant results for all three profiles for at least one of the hydrology variables.

	Variable	Runoff R_{max}	Runoff R_{mean}	Runoff R_{Tot}	Sediment yield S_{mean}	Sediment yield S_{Tot}	Sediment yield S_{max}	Timings T_{start}	Timings T_{max}
Ground cover	Gcp	0.535	0.040	0.228	0.059	0.050	0.309	0.033	0.221
	$EdgeTot_{im}$	0.035	0.001	0.100	0.070	0.107	0.059	0.130	0.011
	Cvb_{im}	0.571	0.052	0.115	0.261	0.286	0.244	0.262	0.441
	B_{im}	0.250	0.015	0.194	0.001	0.005	0.193	0.013	0.036
Slope	UpslpAngle	0.534	0.040	0.228	0.058	0.049	0.309	0.033	0.219
	PltAngle	0.395	0.040	0.041	0.313	0.362	0.137	0.351	0.416
	PltDist	0.381	0.039	0.037	0.314	0.365	0.130	0.355	0.410
	Curv	0.572	0.052	0.115	0.261	0.285	0.245	0.261	0.440
Spatial	Theissen	0.008	0.003	0.030	0.175	0.234	0.003	0.257	0.106
	Fractal	0.393	0.040	0.040	0.313	0.363	0.136	0.352	0.415
Weighted means	VolwMb	0.578	0.052	0.120	0.256	0.279	0.250	0.254	0.439
	AreawMb	0.561	0.051	0.109	0.268	0.294	0.237	0.271	0.443
	EdgewMb	0.529	0.050	0.091	0.283	0.315	0.215	0.294	0.444

Variable name	Variable type	Description
Gcp_{plot}	Plot variables	Percentage clast ground cover – rainfall simulation plot (%)
$EdgeTot_{plot}$		Total edge length (m)
B_{plot}		Mean intermediate axis (m)
PltAngle	Slope variables	Rainfall simulation plot angle (degrees)
UpslpAngle		Mean angle of slope 10 m above plot (degrees)
PltDist		Distance of plot from slope crest (m)
Curv		Slope curvature (and of the slope 10 m above the plot, minus the angle of the slope 10 m below the plot)
Gcp	Image analysis ground cover variables	Percentage clast ground cover – image analysis plot (%)
EdgeTot		Total edge length – image analysis plot (m)
CVB		Coefficient of variation
B		Mean intermediate length (m)
VolwMb		Volume weighted mean intermediate axis length (m)
AreawMb		Area weighted mean intermediate axis length (m)
EdgewMb		Edge length weighted mean intermediate axis length (m)
Fractal	Spatial variables	Box fractal dimension for sediment area
Theissen		Standard deviation of number of vertices of Theissen polygon network

Table 5.5 Correlation statistics – concave profile

Analysis of mean runoff hydrographs generated by the three plots at each of the three slope locations shows a distinct difference between sites (Figure 5.17). The first notable feature of the data is the relative similarity between the plot locations. Top location returns the maximum runoff and greatest volume of runoff. The bottom plot has the shortest lag time in runoff generation, whereas the middle plot has the most muted response.

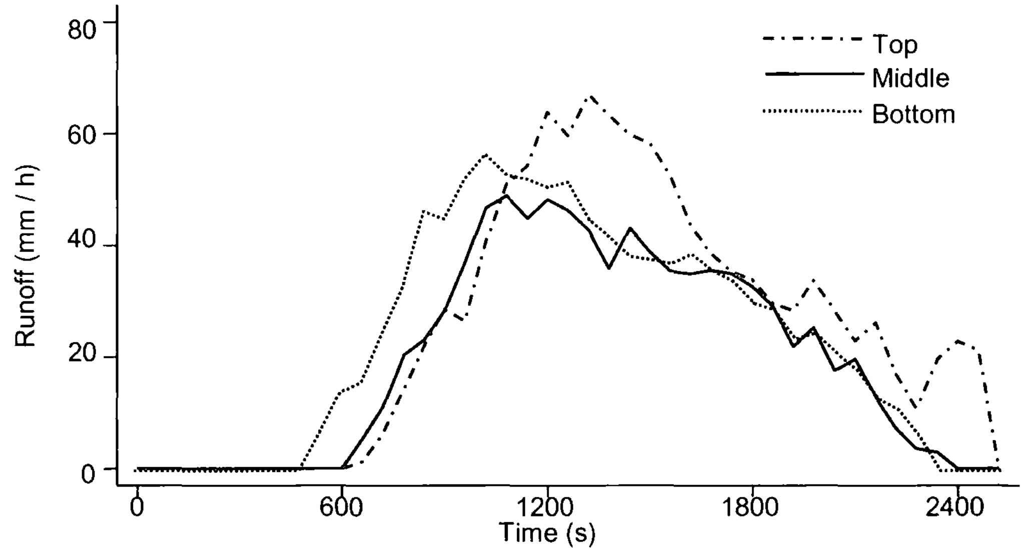


Figure 5.17 Runoff hydrographs for concave profile

The top plot shows a flashy response which closely mirrors the applied rainfall. This is attributed to the low levels of underlying sediment and corresponding low infiltration rates. The high slope angles at the top plot (top mean plot angle = 11.8° (middle mean plot angle = 9.8°; bottom mean plot angle = 7.1°)) promote the rapid removal of standing water. Exposed clasts standing proud of the surface cannot interlock and act to dam water flow as efficiently as part submerged clasts. Variability in hydrological response also varies down-slope. The hydrograph trace for the top and middle plots are arguably more variable than that for the bottom plot location, again showing a more controlled and muted surface hydrology at the base of the slope. The middle and bottom plots show similar behavior, despite having quite different ground surface cover (middle Gcp = 36.8%; bottom Gcp = 40.8%) and slope angles (middle PltAngle = 9.4° ; bottom PltAngle = 7.1°). At the middle plot high slope angles but low cover result in a very similar behavior as low slope angles and high ground cover at the bottom plot. Analysis of standardized means allows further comparison between variables on the concave profile (Figure 5.18).

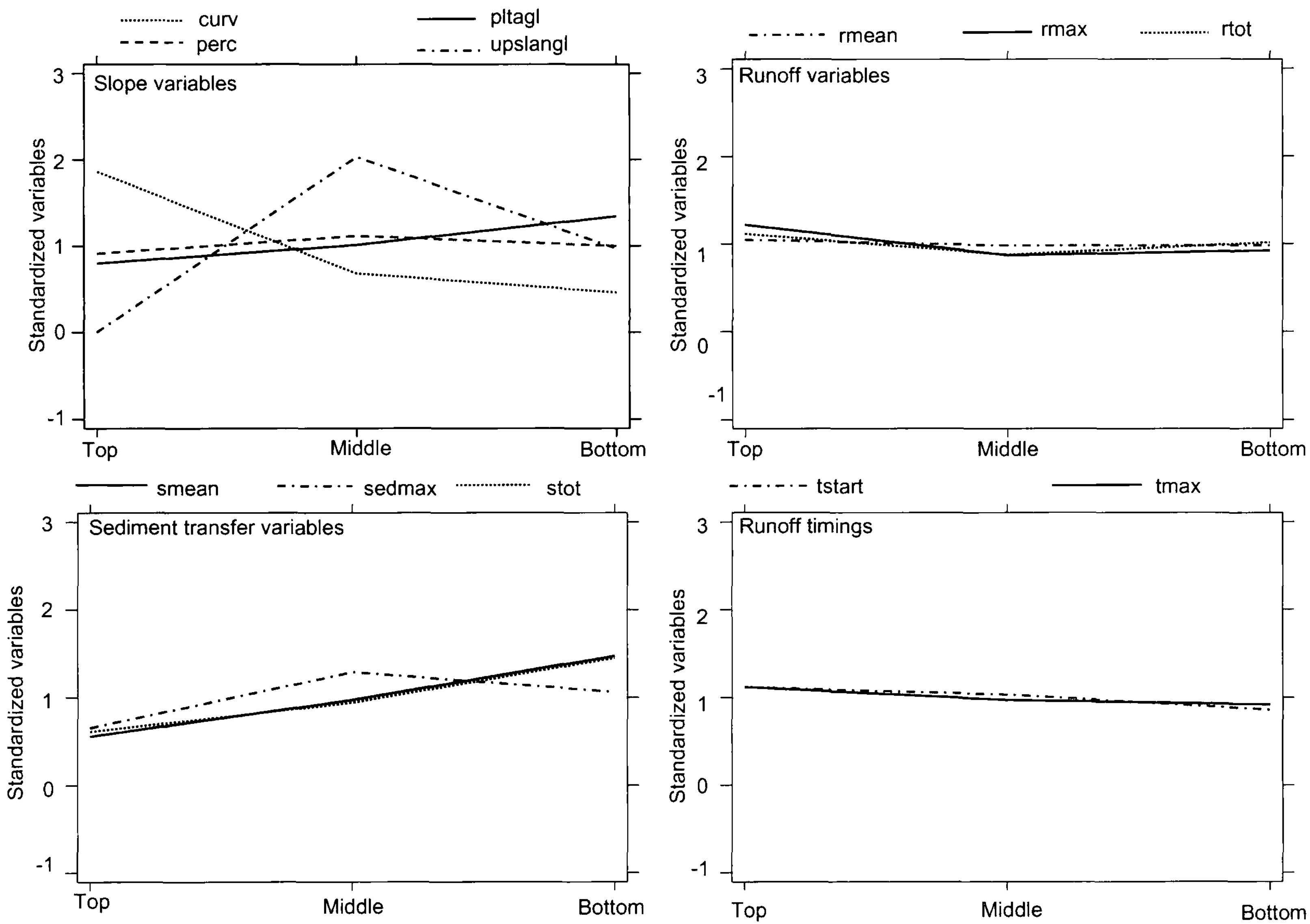


Figure 5.18 Concave profile - standardized variables

Several key trends are apparent that can be explained in terms of the slope profile morphology. Runoff variables are very similar for all plot locations. The most variable of the slope morphology attributes on this profile up-slope angle. Up-slope angle appears to have little direct effect on runoff variables down-slope, though again if anything, runoff variables appear to reduce with increased up-slope angle at the middle plot location. Sediment dynamics show a more complex picture. Maximum sediment load appears to directly link with changes in up-slope angle. Increases in mean sediment yield and total sediment yield also appear to correlate directly with relative increases in local mean plot angle. Runoff and sediment timings appear to decrease down-slope, again possibly suggesting a more muted response at the bottom slope locations.

5.6.3 Convex profile

Analysis of the runoff hydrographs of the convex profile again suggest the nature of change in surface hydrology. The notable difference at this site is the behavior of the middle plot. Here a highly variable and flashy hydrograph is apparent (Figure 5.19).

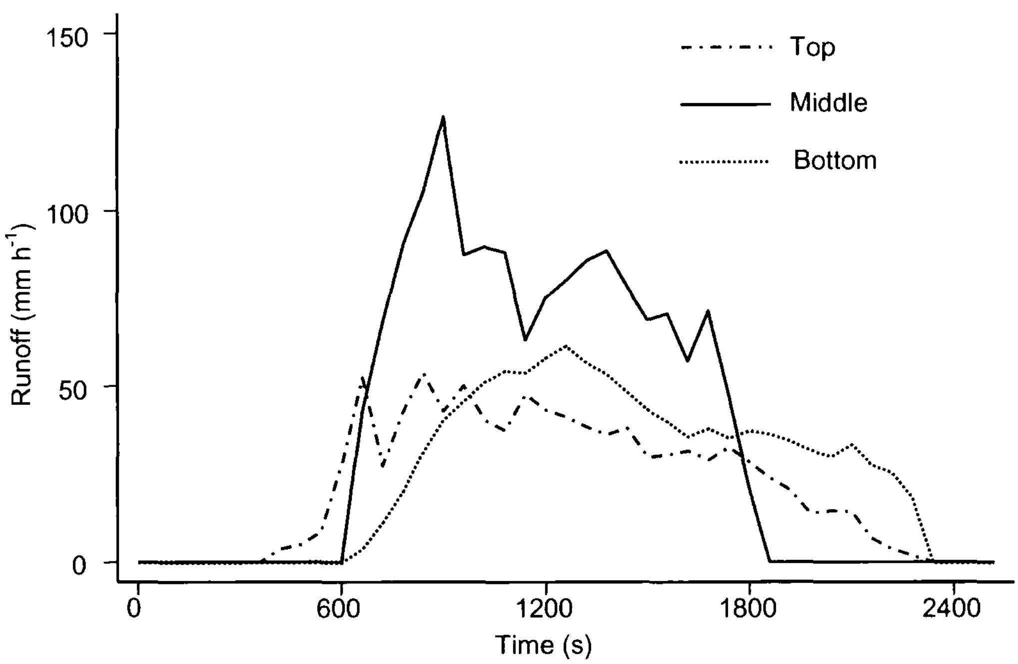


Figure 5.19 Runoff hydrographs for the convex slope profile

In accordance with the pattern seen at the sites discussed thus far the top plot remains responsive, in this case being the quickest to generate runoff. The relative degree of variability in runoff appears to decrease down-slope, with the notable exception of the central plot location. The middle plot location shows the highest levels of runoff and accordingly the lowest levels of infiltration during simulated rainfall. The middle plot also shows the most rapid response to the onset of intense rainfall and conversely quickest cessation of runoff after rainfall ends.

The middle plot on the convex slope is located effectively on the edge of a smooth convex ridge. The up-slope area is an extensive plateau area with low gradients. The curvature of the local slope is highly convex (Curv = -4.2), with an equally high up-slope angle (9.02°). The resulting acceleration of large volumes of runoff collected on the plateau above results in a highly active supply area. This contradicts the previously made suggestion that the further down-slope, the more severe the modification of the surface by process activity, and hence the more muted the hydrological response.

The nature of down-slope change observed brings into question what role the different sections of the slope play. The slope bottom is commonly seen to act as a zone of deposition, with extensive clast burial and surface organization. The crest of the slope acts as a supply zone, whereby there are commonly little or no surface sediments. The role of the central plot location varies with slope form and not just slope angle. In the case of the straight slope the middle plot represents a transition between the top and the bottom of the slope. On the concave profile the reducing slope angle and corresponding change in ground surface cover means that this area is potentially dominated more by deposition. On the convex slope the role of the middle location is reversed. The high slope angles relative to the up-slope section of the slope mean that the middle slope location acts as a supply zone. The surface has sediments transferred from above, in addition to in-situ sediments, all of which are susceptible to removal due to the slope and potential runoff volumes. The complexity of the variations in process action on the convex profile is further reflected in the regression analysis. Again only a limited number of statistically significant relationships are apparent (Table 5.6).

		Runoff			Sediment			TImings	
		R_{max}	R_{mean}	R_{Tot}	S_{mean}	S_{Tot}	S_{max}	T_{start}	T_{max}
Ground Cover	Gcp	0.001	0.149	0.042	0.074	0.040	0.013	0.332	0.375
	$EdgeTot_{im}$	0.433	0.289	0.242	0.323	0.279	0.179	0.002	0.452
	Cvb_{im}	0.014	0.289	0.111	0.177	0.112	0.001	0.376	0.260
	B_{im}	0.401	0.779	0.456	0.657	0.500	0.102	0.227	0.015
Slope	UpslpAngle	0.154	0.006	0.025	0.026	0.033	0.097	0.137	0.569
	PltDist	0.106	0.000	0.007	0.006	0.011	0.077	0.178	0.551
	PltAngle	0.320	0.125	0.131	0.168	0.156	0.152	0.036	0.543
	Curv	0.523	0.592	0.408	0.567	0.459	0.178	0.043	0.232
Spatial	Fractal	0.071	0.009	0.001	0.000	0.002	0.061	0.212	0.528
	Theissen	0.157	0.007	0.026	0.028	0.035	0.098	0.134	0.570
Weighted means	VolwMb	0.141	0.575	0.281	0.422	0.299	0.018	0.378	0.071
	AreawMb	0.235	0.689	0.363	0.536	0.391	0.043	0.339	0.017
	EdgewMb	0.337	0.761	0.427	0.622	0.466	0.077	0.278	0.000

Variable name	Variable type	Description
Gcp_{plot}	Plot variables	Percentage clast ground cover – rainfall simulation plot (%)
$EdgeTot_{plot}$		Total edge length (m)
B_{plot}		Mean intermediate axis (m)
PltAngle	Slope variables	Rainfall simulation plot angle (degrees)
UpslpAngle		Mean angle of slope 10 m above plot (degrees)
PltDist		Distance of plot from slope crest (m)
Curv		Slope curvature (and of the slope 10 m above the plot, minus the angle of the slope 10 m below the plot)
Gcp	Image analysis ground cover variables	Percentage clast ground cover – image analysis plot (%)
EdgeTot		Total edge length – image analysis plot (m)
CVB		Coefficient of variation
B		Mean intermediate length (m)
VolwMb		Volume weighted mean intermediate axis length (m)
AreawMb		Area weighted mean intermediate axis length (m)
EdgewMb		Edge length weighted mean intermediate axis length (m)
Fractal	Spatial variables	Box fractal dimension for sediment area
Theissen		Standard deviation of number of vertices of Theissen polygon network

Table 5.6 Correlation statistics – convex profile

The convex profile returns several significant correlations between R_{mean}, mean clast intermediate diameter and its derivatives. There are also significant links between S_{mean} and T_{max}. No significant correlations (α = 0.1) are apparent between sediment yields. Surprisingly R_{max} appears to be poorly related to all variables. Mean runoff does correlate well with two variables ($EdgewMb_{im}$ and B_{im}). It is interesting the note the reversal of the significance of the weighted mean values in this instance. Both convex and concave profiles fail to return any significant relationships with either slope angle or distance variables. The statistical significance of the samples collected could be questioned. The regressions are based essentially on only three points in space. The methodology discussed in Chapter 3, whereby the sample sites were carefully selected on key type slope profiles and then the image analysis plot and three rainfall simulation plots were statistically chosen as representative of that slope position. It appears that the complexity occurs as a result of slope form variation and not local scale heterogeneity in surface character. The profiles can be considered individually to explain the nature of variation in slope hydrology measured between slope positions.

Additional factors may influence the significance of the results generated. The slope height and length (12.0 m and 46.1 m) are significantly less than on the straight site. Therefore overall volumes of runoff generated due to the reduced up-slope catchment area may result in less differentiation in form and process between the extremes of the slope. Systematic variability may therefore be subjected more to the natural levels of heterogeneity in surface behavior.

Aggregated statistics and linear regression are not sufficient to understand the variation in surface hydrology observed between points. Standardized means again give a further insight into the relationships between slope variables (Figure 5.20). The convex profile presents a massive variation in profile curvature between plot locations. Additionally, a significant variation in up-slope angle with distance down the slope profile is apparent. The magnitude of the variation in up-slope angle may be reflected in a similar magnitude of variation in surface hydrology. Runoff variables are all at a maximum at the central plot location, supporting the claim that this area is strongly influenced by the up-slope catchment and high local slope angles. Additionally, sediment yield variables appear to mirror changes in up-slope angle. An increase in up-slope angle reduces the mean sediment load, total sediment yield and to a lesser extent the mean maximum sediment load. Time to runoff increases slightly at the middle plot location, and reduces at the slope bottom. Time to maximum runoff increases down-slope.

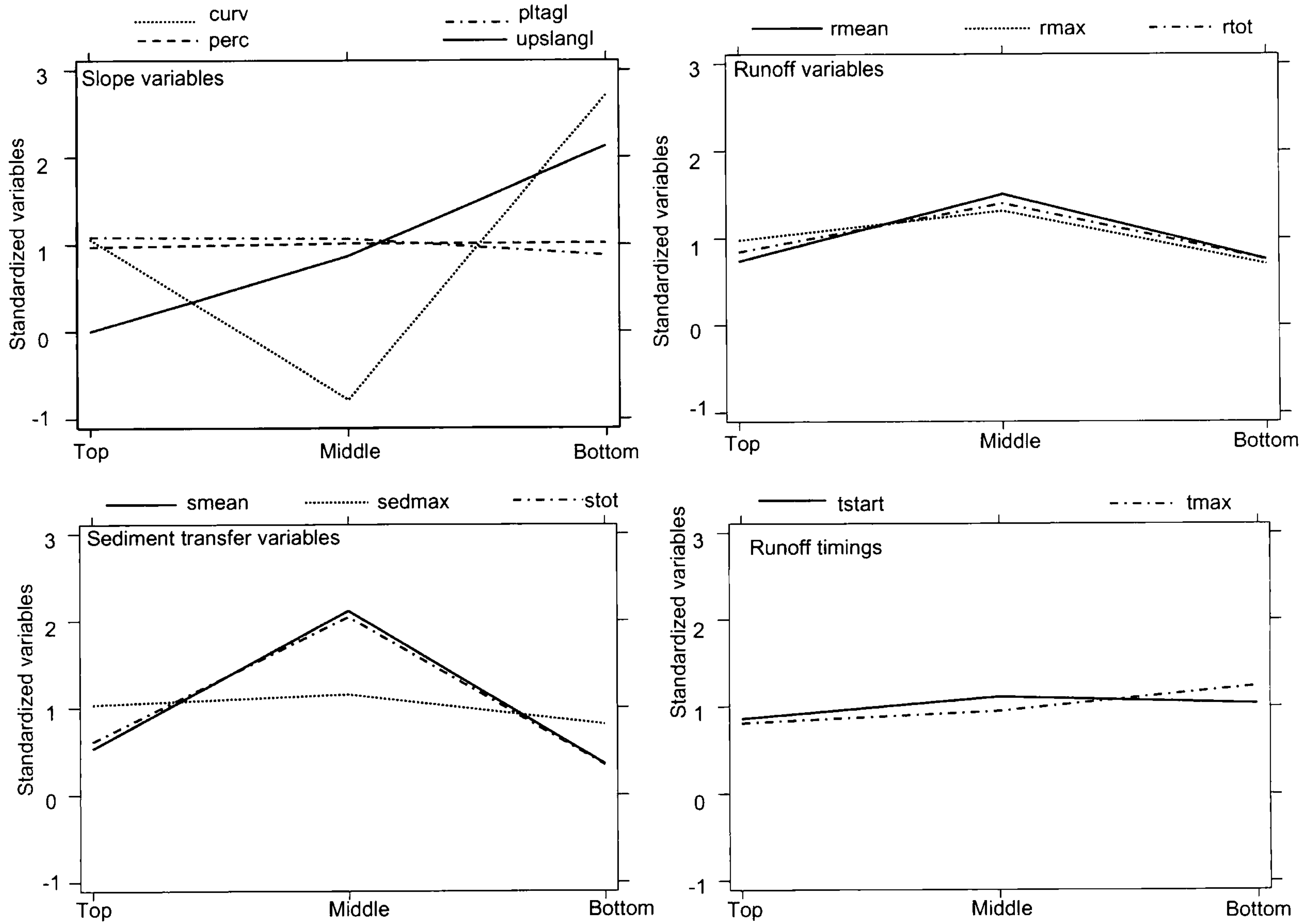


Figure 5.20 Convex profile - standardized variables

5.6.4 Combined influence of slope and ground cover on surface hydrology

The results generated from the analysis of individual plot locations reveal a complex series of relationships between ground cover, slope and surface hydrology. The interdependencies between variables change with the position of the plot on the slope profile. The feedbacks between form and process further complicate the nature of down-slope change. In order to draw generalized conclusions with regards surface hydrology, exploratory multiple regression was undertaken on the variables which have been previously identified as influential. This approach yields significant results.

The variables which returned the most significant correlations during linear regression analysis were used in the multiple regression. Models were generated to assess the degree to which the variables of slope hydrology variables derived from the rainfall simulation. The significance of the regression models was further enhanced by the inclusion of the Pltdist variable, which potentially acts as a surrogate for other facets of the slope geomorphology (Vincent and Sadah, 1995). The results of the multiple regressions are presented below in Table 5.7.

	Hydrological variable	Curvature	CVB	Theissen	Pltdist	constant	Prob > F	R^2
Runoff	Runoffmean	-2.102	2.518	46.385	-0.094	-75.384	0.000	**0.763**
	Runoffmax	-2.184	2.632	11.198	-0.175	-7.892	0.000	*0.591*
	Totalrunoff	-149.659	184.052	1784.413	-8.860	-2512.2	0.003	0.496
Sediment	Sedmean	-0.003	0.003	0.046	0.000	-0.066	0.511	0.133
	Sedmax	0.001	-0.009	0.327	0.000	0.264	0.847	0.058
	Sedtotal	-0.060	0.061	-0.149	0.004	-0.282	0.839	0.060
Timings	t_{start}	-0.063	0.227	11.432	0.008	-8.571	0.113	0.278
	t_{max}	9.242	23.280	844.696	1.804	-700.78	0.001	0.553

α = 0.05 – **bold**, *α = 0.1 - italics*

Table 5.7 Multiple regression analysis between slope, ground cover and surface hydrology variables

Three significant multiple regressions are apparent. It is interesting to note the hydrological indicators which correlate well with the applied regression. Sediment dynamics all show poor and inadequate r^2 values. The runoff variables all provide promising regression, two of which are statistically significant. Using multiple regression analysis it is apparent that mean levels of surface runoff can be statistically linked with confidence to slope, ground cover and an understanding of the spatial character of the surface clast distribution. The ability to predict runoff generation from ground cover and plot will allow a much greater understanding of surface dynamics and evolution. Additionally, time to maximum runoff is well predicted by this model. Analysis of heteroskedasticity, using a Cook-Weisberg test, returns a high probability (0.604), suggesting the residuals are not heteroskedastic. A variance inflation test for collinearity suggests a tolerance of 0.222, and residuals compare well with a normal distribution. This apparent independence between variables has interesting implications for understanding the interrelationships between variables. The importance of each variable is shown by a significant reduction in the r^2 value when any of the variables are removed from the model.

Combined multiple regression therefore returns greater levels of significance than a consideration of single linear regression between runoff and slope form or ground cover variables. This provides a valuable insight into slope hydrology in the Badia, which is now discussed below.

5.7 Discussion

The rainfall experimental undertaken in this study provides the first insight into slope hydrology on the boulder mantled surfaces of the northeast Badia. Distinct spatial variability between contiguous and disparate locations has been identified. Variability in surface hydrology can be systematically linked with both conventional measures of ground cover in addition to new types of data generated with the image analysis, in addition to slope form. For example, in several instances the spatial data concerned with the relative arrangement of surface clasts correlates with a greater degree of significance with changes in surface hydrology than conventional measures of surface form. Several interesting facets of the landscape have been identified.

The rainfall simulations show that splash detachment plays a critical role in dictating sediment mobilization. Hydrological response to applied rainfall is increasingly muted with distance down-slope. The variation in surface hydrology is a reflection of not just ground cover, but a combined influence of slope and ground cover variables. Hydrology at a point on the slope is dictated by not only the local conditions, for example ground cover, but also by the situation of that plot within the context of the whole slope profile. The relative position of a point on a profile links with both slope form and local slope angles. The measures of plot distance down-slope and slope angles perform as variables indicative of altered surface form which is in turn dependant on slope control. The reworking of sediments is suggested here as a critical control on this variation.

Sediment movement is linked directly with overland flow hydraulics and hence hydrology. Increased runoff volumes act to increase the transport of surface sediments. Where flow velocities reduce, deposition increases. It has been shown that hydrology is influenced by ground cover. It is suggested that ground cover is influenced by surface hydrology, via the reworking of sediments. Deposition of sediments to areas of ponded water is instigated by lower slope angles and structured clast cover which acts to inhibit flow processes, supported by disparities between ring infiltration and rainfall simulation experiments. The ring infiltration indicates a decreasing level of infiltration down-slope. The rainfall simulation similarly suggests a decreasing level of infiltration at the base of the slopes, which can only in part be attributed to a slight increase in infiltration capacity. Slope base hydrology is generally characterized by a greater level of standing water and ponding. Factors that influence the occurrence of ponding include slope angle and the spatial arrangement of surface clasts. Where polygonal networks in the clast surface arrangement are apparent, they act to dam surface water, increasing ponding depths.

The processes identified at the scale of the rainfall simulation experiments are seen to be of insufficient magnitude to modify the boulder surfaces over anything other than large timescales. The experiments by their nature and extent are not sufficient to generate the magnitude of process action to move clasts by direct transport action. The apparent control of clast cover on surface hydrology, either directly or indirectly, suggests that flow velocities would never reach the magnitude sufficient to transport clasts by entrainment, and there is no evidence in the field of this. This adheres to Cooke's (1972) suggestion that although overland flow and slope hydrology may maintain the character of contemporary pavement surfaces, they cannot, by definition, be the process primarily responsible for their initial formation (Vincent and Sadah, 1995). The development of the surfaces is more complex than purely based hydraulic transport of surface clasts, or runoff creep (Abrahams *et al.*, 1994).

Surfaces appear to be well drained. There appears to be a good degree of connectivity down the slope profile with evidence of lateral drainage into preferential flow paths. Flow pathways are not common. To support this Hortonian overland flow tends to promote rill and gully development (Horton, 1945), where flow becomes concentrated as dictated by microtopographic variations. No rill or gully networks are apparent in the northeastern Badia. Depth, velocity and routing of overland flow are controlled by the roughness of the clastic surface. Movement of clasts and adjustment of the spatial nature of the surfaces by hydraulic action therefore appears unlikely. There is some evidence to suggest hydraulic transport of clasts does occur in areas of concentrated overland flow but this does not account for the uniform cross contour nature of down-slope change in ground cover identified by the image analysis. An alternative method of surface adjustment and clast transport is suggested.

Several features of the surface indicate that the nature of change in ground cover is as a result of iterative process action. Complex interactions between multiple factors have all been shown to influence slope hydrology. The nature of the interactions between slope, surface and process varies. Slope, surface and process activity are all interdependent. The nature of change of both surface form and process response is often found to be gradual down-slope and continuous across the contours of the slope profile. The case for iterative process action and surface adjustment is further supported by the nature of the surfaces. The distribution of clasts on the surface is surprisingly continuous, given both the absolute age and the range of ages of the surfaces. The massive nature of the surface clasts suggests that they can rarely be moved by flow processes. Poesen (1987) identified that clasts up to 0.1 m in diameter could be transported by concentrated overland flow processes. Movement by shrink, swell and resettling of the underlying sediments, or even ice needle action seems more feasible. The iterative modification of the surface is suggested to be in part at least dictated by slope hydrology. Slope angle influences the tendency for a lifted clast to resettle down-slope during a swell cycle. Ground cover influences the degree to which clasts contact and lock together. Up-slope angle, down-slope distance and slope curvature, potentially influence the modification of the local surface by dictating the intensity of process action at that point. Slope angle is a control on more than just the rate of process action, as is conventionally used in slope hydrology. Surface patterning could also be suggested to play an important role here. If a locked structure acts to dam the flow of water, then infiltration may increase as a result of the increased levels of standing ponding. If enhanced infiltration into the surface increases the degree of shrink and swell and surface modification, then a patterned surface may tend to self-perpetuate its own form, via a positive feedback. This may explain the visual assessment that in many instances there either clear structure and pattern, or conversely no pattern at all. This suggestion is not supported by the gradual down-slope increase in surface organization identified by the image analysis (Chapter 4). Factors which positively influence such modification, for example, those which encourage iterative clast movement, can be seen to self perpetuate.

An example of this is the redistribution of coarse surface fragments by rain splash impact, as was witnessed in many of the experiments undertaken. Exposed sediment areas undergo rainfall impact which acts to detach coarse surface fragments. A tendency for these fragments to relocate in the shelter zones around the sediment contact perimeter of clast was noted, especially where surface clasts remain exposed from the sediment surface. Analysis of wetting fronts relative to coarse sediment surfaces and exposed clasts suggest a greater degree of infiltration into the surface; a factor that is supported by the increased infiltration rates generated by the rainfall simulation. With increased infiltration in the subsurface sediment, the greater the degree of clay swell and hence the greater the magnitude of clast uplift. Clasts then settle with gravity, potentially fractionally moving down-slope and raising themselves though the sediments, affording more shelter for the accumulation of surface fines. Clast settling is a gravity driven process, an acceleration force and hence undergoes a geometric rate of change. Any variability in surface behavior is therefore exacerbated though surface form adjustment.

The changes in surface character identified by the image analysis are not all focused on the movement of clasts. Evidence is also presented that shows increasing rounding and smoothing of clast texture down-slope. The nature of clast shape alternation can be explained by the assessment of the surface hydrology. Increased volumes of water at slope base increases the down-slope potential for attrition and abrasion by entrained sediments. Clast sorting was shown to relate well with slope angle. Here the influence of up-slope angles is suggested to influence local runoff velocities and hence preferential removal of the finer clast from the surface.

5.8 Conclusions

Several conclusions can be drawn with regards the hydrological behavior of the surfaces of the Badia.

1. Surfaces appear to be active. Links between surface form, slope and process suggest a close synergy between variables showing that the surface activity adjusts and responds to present day process action.

2. Surface hydrology is highly variable between locations but can be linked to slope form and ground cover.

3. Understanding the hydrology of whole slope profiles appears to be important. Any generalized understanding of slope hydrology must take into account the degree of variability in slope hydrology as influenced by ground cover and slope form.

5. Slash detachment is a dominant control on sediment entrainment and mobilization.

6. An assessment of the spatial nature of surface clast distribution yields significant correlations with surface hydrology. Surface organization is therefore a vital control and effect on slope hydrology. In turn, the presence of surface organization appears to be systematically linked to slope processes.

7. Sediment yields, under even high rainfall intensities, are low. Significant and rapid re-deposition of large volumes of sediment only occurs as a result of hydraulic detachment and deformation of the sediments in areas of concentrated overland flow.

8. The presence of surface clasts dictates the nature of slope hydrology.

9. The local hydrological response of the surfaces decreases down-slope. Process intensity, in terms of up-slope catchment area and presumably increased flow depths and velocities, means that process action is greatest towards to toe of slope profiles. Process modifies form. The most significantly modified slope locations at the base of the slope are less responsive, suggesting a negative feedback loop, acting to diminish or mute the influence of flow processes.

10. The slopes of the Badia are not necessarily dominated by high-magnitude low-frequency events, but may be more sensitive to the iterative action of high-frequency low-magnitude variations than previously suggested.

The results presented above give a detailed insight into slope hydrology. The dominant processes which act to modify the surfaces and the ground cover characteristics may not be hydraulic. Direct measurement of iterative processes over the time scales involved in the Badia is not feasible. In order to understand the dynamics of surface modification a different approach is required. The next chapter builds on the data generated from the characterization of ground surface variation and the appraisal of surface hydrology presented in this chapter and examines the suitability of considering the surfaces to be dictated by iterative, alternation processes.

Chapter 6: Modelling the development of coarse clastic surfaces in arid environments

Chapter 6: Modelling the development of coarse clastic surfaces in arid environments

6.1 Aims and objectives

This chapter aims to simulate the spatial modification of coarse clastic desert surfaces as a self-organizing system. In doing so, an iterative mechanism of clast surface modification is tested. Clast surface modification and movement is clearly apparent in the northeastern Badia but an understanding of nature of surface clast movement is limited due to the rates and scales of modification of contemporary surface forms. A computer simulation approach is presented in this chapter which aims to build upon the findings of the surface characterization and process studies. The purpose of the model is to test ideas of self-organization as a method of understanding surface dynamics in the northeastern Badia.

The first part of the chapter outlines the nature of characteristics of the surface which indicate the nature of surface dynamics in the northeastern Badia, in the light of evidence presented in Chapters 4 and 5. The section highlights the features of the surface which lend themselves to a modelling approach to explore the nature surface dynamics. A discussion of similar coarse clastic systems in geomorphology follows, providing a discussion of the methods employed in modelling the dynamics of such systems. An appropriate modelling approach is then developed. The nature of the surfaces lends themselves to a cellular modelling approach. The model is used in a parametric study, which assesses the sensitivity of the model to variation alterations in starting conditions and controlling variables. The variables used in the parametric study are selected upon their ability to represent specific geomorphological variations noted in the northeastern Badia in this thesis. The model output is compared to geomorphological phenomena observed in the northeastern Badia and raises several key questions for understanding the geomorphological evolution of the surfaces.

6.2 Background

The surface features of the northeastern Badia are indicative of the processes which have lead to their formation. Significant relationships have been identified between surface processes and surface forms (Chapter 5). The apparent organization that the surfaces exhibit is a peculiar geomorphological phenomenon which has not been previously been documented. Mechanisms of surface modification appear to be complex. There is both a modification of the nature of the individual clasts, in addition to the alteration of the spatial arrangement of surface clasts. Subtle links between form, slope and process have been detailed in many aspects of contemporary surface character. The action of surface processes appears closely linked to variation in ground surface form and slope. In some instances the nature of surface form remains vexing. Surfaces with similar ground cover, slope and clast form commonly exhibit different spatial arrangements of clasts. Some form of spatial modification or reorganization of the surface is therefore happening. Geomorphologically, the departure of the arrangement of surface clasts from a completely random distribution holds a significant influence over flow routing, hydraulics and hydrology (Abrahams and Parsons, 1991; Jean *et al.*, 1999). In a theoretical context, the presence and apparent systematic variation of clast surface organization, patterning or structure is an indicative characteristic of a self-organizing system (SOS) (Phillips, 1999). If self-organizing systems are an appropriate method of understanding the surfaces of the northeastern Badia, then the results of this model of surface dynamics has many implications for the contemporary geomorphology.

In the light of the results discussed in Chapter 4 and 5, a greater understanding of the processes in action and the processes responsible for the formation of the clastic surfaces of the northeastern Badia can be made, which helps in the design of a modelling approach. Subtle variations in land surface configuration and process action on the slopes of the northeastern Badia have been shown both in this thesis and elsewhere (Allison *et al.*, 2000). A close symbiosis between form and process is evident. The nature of interactions between clasts is complex and varies between locations, with no obvious overriding control of one individual or single set of variables, commonly manifested through non-linear behaviour. By their nature the controls on surface form and process interact. They influence and are influenced by each other. The apparent control afforded by the clast surface on hydrology suggests that the mechanism of clast movement is likely to be a result of iterative small scale movements, rather than large scale displacements during catastrophic events. Given the age of the surfaces, the small scale movements may only occur after what in the present context is a high-magnitude event but over the timeframe of whole surface development these events can only be considered a small-scale iterative change. Constant climatic forcing is unlikely to have been the case in this region (Chapter 2), so the temporal change in surface character may have been more complex.

Several potential movement mechanisms of clasts exist, based upon field observations (Chapter 2). The nature of the movement of surface clasts is controlled by features of the surface which can be approximated to only a few factors. The features can be modelled without a significant degree of over simplification. The surfaces of the northeastern Badia also exhibit some surprising and peculiar features. Clast cover has been shown to have a non-random distribution, often demonstrated through the presence of structures and patterns on the surface (Plate 6.1). The features can be thought of as locking structures, governed by clasts coming into contact and jamming into fixed positions. It is this type of features which is suggested to be indicative of a SOS.

Plate 6.1 A non-random clast arrangement

The assessment of the northeastern Badia landscape in this study has highlighted several parallels between the behaviour of this environment and that of systems which are believed to show a tendency to self-organize. This includes a non-linear relationship between slope, surface and hydrological variables (dynamics), the presence of structure or pattern (emergence) and evidence of negative feedback mechanisms which modify form / process interactions. The suggestion of a homeostatic relationship between form and process has been raised in the context of the northeastern Badia (Higgitt and Allison, 1999a) and in the wider and more general context of desert pavements (Wainwright *et al.*, 1999). The nature and behaviour of the northeastern Badia slopes is complex. Multiple interdependent factors appear to dictate the form and behaviour of the surfaces, which through a reductionist approach, cannot easily be understood. Statistically significant relationships have been identified in this thesis but the degree of variability and unexplained deviation persists between both locations and the methods of surface characterization. The presence of pattern and the variable nature of surface organization have shown more significant relationships between form and process than conventional measures of surface character in several instances. The combination of these results with the observation of spatial organization suggests that considering the surface as a SOS may yield a more detailed understanding of surface form variation, which is beyond explanation using a simple reductionist approach. The comparison of the model output to the slopes of the northeastern Badia and other similar geomorphological situations, allows further discussion of self-organizing systems in geomorphology.

6.3 Modelled structures on clastic surfaces

Regular and geometric arrangements of surface stones, similar in appearance to those in the northeastern Badia, are common features of many unvegetated alpine and polar hillslopes (Werner and Hallet, 1993). The principle feature of the landforms is the marked order which contrasts with the apparent disorder of the natural world. These surfaces are considered sorted due to the characteristic textural distinction between the surface stones and finer soils or sediments beneath. The presence of pattern or structure has been observed in several environments, many beyond the periglacial environment (Schweinfurth, 1964; Rohdenburg and Walkther, 1968; Rolshoven, 1976; Washburn, 1979; Wilson and Clark, 1991). The diversity of environments in which structured features are found reflects a diversity of processes responsible for their formation (Ahnert, 1994). For example, Ahnert cites features at the hot springs at Waiotapu on the North Island of New Zealand, where the periglacial processes responsible for the formation of sorted alpine stripes are not in action. With such diversity in forcing mechanisms, the consistency in the resultant form suggests that the actual process that instigates movement is irrelevant to the final form. Alternatively, it is the resulting movement and interaction of the systems components that is of far greater importance in dictating the final form. There is also evidence to suggest that pattern forms are dynamic, whereby form changes on a seasonal basis. Structure may therefore be more accentuated at certain times of the year. If structure is sensitive to climate as suggested, then structure may also alter with variations in process action, inferred by topography, for example. Topographic controls are known to influence the form of periglacial stripes (Hall, 1998). Pattern is therefore not a discrete entity, but rather a continuum between structure and disorder (Ahnert, 1994).

Several computer based simulations of sedimentary structures have been developed (Naden, 1987; Anderson, 1990; Werner and Fink, 1993; Werner and Hallet, 1993; Ahnert, 1994; Tribe and Church, 1999). The simulations aim to study the development of natural structure or surface modification, as a result of process action that dictates the frequency and nature of clast interactions. By simulating boulder pattern as a series of stochastic movements, the development of surface forms can be assessed.

Ahnert (1994) developed a random walk model, such that the probability of each stone moving location is determined by the status of neighboring cells. Ahnert (1994) bases his model on locking rather than friction. Once a clast is in locked by other clasts its position is static and cannot be moved. A clast is considered locked when neighboured by two clasts that when combined form either a straight line or an obtuse angle. Ahnert's model is based on a surface with negligible gradient and hence the direction of clast movement is random. Ahnert (1994) found that the nature of the initial distribution of clasts is not important as a control over the evolution of the surface. Cover dictated the nature of pattern formation and the speed with which the surface established what is considered to be a stable state. His model does not consider the influence of variable clast size and the variable frictions and movements associated. The model is successful in replicating the structures which the authors observed in the field, but as Tribe and Church (1999) point out, there is currently no rigorous measure of similarity between two-dimensional patterns.

Tribe and Church (1999) adopt a more complex approach to simulating gravel bedforms, again using an iterative kinematic simulation of object movement. Bedload clasts are represented by a population of rigid circular disks of various sizes which undergo elastic collisions without transferring momentum, such that there is no knock-on effect between clasts. Clasts again lock into position, here dictated by the angle with which they contact immobile clasts. Clasts can be deflected or rotated around immobile clasts which simulate processes of entrainment and deposition in fluvial systems closely. A nature of clast movement which considers momentum transfer is perhaps not suitable to boulder mantled surfaces, where movement is suggested to be iterative. Tribe and Church's (1999) model successfully replicated the formation of stone lines and clusters, whose morphology could be related to percentage ground cover transport direction relative to flow.

Several models have examined the development of periglacial sorted networks. Although similar in appearance to the features seen in the Badia, the features are quite different. Periglacial stripes form as a result of cryoturbation, powered by freeze thaw cycling in the sub-arctic environment. The sorting is more of a product of vertical convective displacement rather than a predominantly lateral lock of clasts. An example is the three-dimensional model proposed by Kressler *et al.* (2001), which uses ice crystal growth, thawing, soil compression, desiccation and relaxation of slope morphology and vertical sorting via illuviation. The model is successful in producing sorted circles in three dimensions. Further examples of models to simulate regularity in surface forms have been developed, many based on a cellular automata approach. They include studies of banded vegetation patterns (Dunkerley, 1997), rainfall runoff modelling (Puigdefabregas *et al.*, 1998) and rill initiation and growth (Favis-Mortlock *et al.*, 2000). Despite the limitations of a modelling approach, these studies all provide alternative explanations or reiterate field and laboratory studies of complex process action.

6.4 Theoretical background to self-organizing systems in geomorphology

It is necessary to give a theoretical background to self-organizing systems and then expand the considerations to the geomorphology and earth surface systems. Self-organization as a concept has evolved considerably. As a theory applied to geomorphological situations there are several factors which limit its application. The most pertinent of these are first, the lack of quantitative validation to the field, and second, a dissatisfaction with the precise definitions of self-organization. Some to suggest research into chaos, fractals and self-organization has passed its peak (Baas, *in press*), but its development and application continues. Due to the evolving nature of its use, inconsistencies exist in the definitions of what exactly constitutes a self-organizing system. Several comprehensive reviews of self-organization applied to earth surface systems (Phillips, 1999), the recognition of the emergent properties of landforms (Harrison, 2001) and self-organized criticality (Bak *et al.*, 1988), give greater historical and theoretical depth than is necessary here. The use of self-organization within geomorphology has been directly adopted from other scientific disciplines. It is these disciplines that are used as basis for description of the background and definition of self-organizing systems;

> "[...] a self organizing system is a system which tends to improve its performance in the course of time by making its elements better organized for achieving a goal. This includes the special case in which the goal is to achieve a high degree of complexity (order) of relevant entities from a low degree of organization (disorder, chaos)." (Klir, 1991 page 156).

Self-organization refers to the spontaneous formation of organized structure or pattern from initially random conditions, a process termed emergence (Harrison, 2001). The emergence of structure has often been attributed to an equalization of entropy across the landscape (Phillips, 1999). A self-organizing system will alter its structure depending on its experiences and its environment (Farley and Clark, 1954). Several similarities are apparent between many physical and biological systems, which have intelligence and memory (Phillips, 1999). A system is a collection of interacting parts that function as a whole. It is distinguishable from its surroundings, with recognizable boundaries. A system has properties that are emergent. They are not contained within any of the individual parts. They exist at a higher level of description. Self-organizing systems are considered adaptive and dynamic. Dynamic systems are composed of a large number of elements and thus the system occupies a very large state space. The elements interact, commonly termed synergetics (Haken, 1977). The size of the state space, the total number of arrangements or combinations available to the system, is considered to increase in dimension in accordance with the number of variables (Lucas, 2001). Self-organizing systems evolve to occupy a smaller volume of their state space tending towards an attractor, which is interpreted as a form of self-organization. The presence of an attractor in a system is only identified under conditions whereby energy is dissipated, through for example friction. Dissipative structures therefore only exist when there is a constant flux of energy through a system. In the case of geomorphic systems, flux maybe periodic as dictated by geomorphic events, but is still considered constant.

Self-organizing systems are not in equilibrium, but are dynamic. An attractor maybe chaotic, under which condition the emergent behaviour is often too complex to understand, or it may be confined to a small region of the state space. Under this condition order and structure of a consistent nature will form from initially random conditions. Formal dynamic systems are commonly used to understand real dynamic systems, for example networks of chemical reactions and non-equilibrium thermodynamics behaviour (Nicolis and Prigogine, 1989). The conclusion from much work with self-organizing systems is that there is a tendency for the spontaneous formation of complex physical patterns in nature (Kauffman, 1993). The process of self-organization is commonly interpreted as the formation of order from chaos. The evolution to order is pre-constrained by the position of the systems attractors in state space and unless the parameters of a system are changed, a system cannot deviate significantly from its own attractor landscape. Evolution is constrained in a self-organizing system (Inkpen and Petley, 2001) a suggestion which runs parallel to Brunsden's (2001) suggestion of landscape resistance, dictated by the system structure, its history and the way in which a system filters energy movement across the landscape.

It has been long established in ecology that the nature of spatial pattern directly influences the action of processes (Wat, 1947, Huffaker, 1958), so the extension of this to earth surface systems appears logical. Self-organizing earth surface systems exhibit unique attributes. Self-organization involves interactions which are commonly manifested as reversible, two way processes. In earth surface systems one way processes are of importance. Gravity driven flux of energy and mass, for example the down-slope migration of sediment due to toppling or weathering processes, further act to complicate the nature of a systems dynamics and make their emergent forms recognizable. The features of earth surface systems do not detract from the suggestion that they are undergoing self-organizing process.

Given the inherent diversity and complexity of natural systems, a series of characteristics of self-organizing systems can be suggested, though still no definitive laws are available. The system must be considered to be thermodynamicly open, in that it exchanges energy with its environment. The system must exhibit dynamic behaviour such that it is undergoing constant or iterative change. An example of this is the import of usable energy, for example an increase in potential by heave processes instigated by the action of hydrology and the export of entropy back to the system, although parallels between the laws of thermodynamics and the behaviour of physical systems is not supported by all (Shalizi, 2001).

A self-organizing system undergoes inherent local interactions whereby neighboring objects and systems directly influence each other. Self-organizing systems exhibit non-linear dynamics as a result of the action of positive and negative feedback loops. Feedback can exist between components and between the components and the structures that emerge. A self-organized system must contain many parts as the behaviour of the system is determined by the interactions, connections and feedback loops between the systems parts. Emergence, arguably the most nebulous concept of self-organizing systems (Crutchfield, 1994), is based on the suggestion that the whole system is greater than the sum of the parts. The effects of self-organization are multi-scale. Small scale interactions can result in large scale emergent structures which then in turn act to modify the nature of the small scale interactions. Prigogine (1984) suggests that large scale emergence is a way for a system to dissipate micro-scale entropy. Macroscopic emergent order maybe indicative of iterative small scale decreases in entropy.

Even under the conditions self-organization may still not occur. The conditions that are sufficient for self-organized behaviour and the necessity of these conditions still remains unknown (Milne, 1996). Accordingly, the effects and magnitude of self-organization remains equally vexing. Dissatisfaction with self-organization often stems from both the weak definitions and the difficulty of quantifying what is in essence a qualitative outcome. Various methods including entropy, dimensionality, computational mechanics, information theory and language theory have all been suggested as methods of describing emergent structure. No one satisfactory method has as yet prevailed.

Self-organization as a method of understanding complex systems has several benefits. Simplicity is critical. The individual components of a system are simple. Complexity only emerges when multiple components interact, but they do this under highly controlled and definable conditions. Basing the behaviour of a system's components on physically based principles is relatively easy and justifiable. Self-organizing systems are in essence reliable. Even though their behaviour is complex, under the same conditions a system will consistently generate a similar type of complex behaviour. As the emergent behaviour of the system is the product of many individuals, the dynamics of a system do not heavily depend upon one individual component. In chaotic systems, the converse applies. A small perturbation can result in massive divergence in a systems behaviour. Finally, self-organizing systems are adaptive. A system may experience variations in external forcing but adapt its character accordingly.

Phillips (1999) suggests that self-organizing systems are commonplace in geomorphology and their use as a mechanism of understanding is by no means new (Haff and Werner, 1996). Some suggest that a landscape or landforms exhibit features that are *greater than the sum of its parts.* A reductionist approach will, if this holds true, struggle to explain the full complexity of landscape (Phillips, 1992). An example of emergent structure in geomorphology is periglacial sorted nets. Their form, structure and morphology cannot be discerned from a minute study of the individual parts, but rather from the interactions between the parts (Hallet, 1987). Other examples include rill initiation (Favis-Mortlock *et al*, 2000), patterned ground (Nicholson, 1976), cuspate beach forms (Werner and Fink, 1993) sand ripples and gravel bed river forms (Tribe and Church, 1999), particle sorting due to vehicles (Perez, 1991). Emergent properties are in essence qualitative structures arising from quantitative processes (Harrison, 2001). It is the description of these emergent properties in geomorphology that some suggest has the potential to explain landscape at the scale of the landform, in such a way that a reductionist approach could never achieve (Harrison, 2001). The local rules that determine a systems dynamics are easily quantifiable but emergent structure is more subjective as it cannot be explicitly described in physical terms.

Many of the features of self-organizing systems theory appear to have significant parallels with the form and potential dynamics of the slopes of the Badia. Under the hypothesis that the slopes of the northeastern Badia behave as a self-organizing system the following points can be suggested.

1. The individual clasts are the components of a larger system. The movement of each clast, under whatever mechanism, be it hydraulic or an iterative heave process, is determined firstly by the components specific character and secondly by the nature and character of its neighboring clasts.

2. Emergent forms are apparent and evidence of modification of the surface has been described. The image analysis of the spatial character of the surfaces has highlighted that the distribution of clasts is non-random. Evidence of clear spatial structure has been witnessed and quantified. Pattern appears to vary with slope and surface cover variables but behaviour appears complex. Results generated from the image analysis and surface hydrology experiment do not appear sufficient to explain the presence and magnitude of surface organization. The explanation of this patterning appears to be at a higher level of description. Organization is also apparent in the diverse spatial nature of surface cover. Evidence of modification of the surface by process action and conversely the action of surface form modifying process action has been illustrated above. This is potentially a manifestation of multi-scale emergence. Evidence of homeostasis acting between form and process is suggested (Higgitt and Allison, 1999a).

3. The surfaces appear dynamic. The present geomorphology of the Badia has shown subtle but significant linkages between contemporary surface character, contemporary process and slope form. A symbiotic link between the contemporary form and process in the context of the historical condition of the slope is suggested.

4. Surfaces appear adaptive. The ubiquitous clast cover in the northeastern Badia is surprisingly continuous despite the massive range of surface ages. The suggestion raised from this is that the surfaces of varying ages have undergone a variety of external forcing regimes but the surface has maintained a surprisingly consistent form, which is still maintained today. Within this ubiquitous clast cover there are subtle variations which are seen to link systematically with slope process action. There are very few areas in the northeastern Badia where the surfaces are substantially different. Virtually all areas of the ground surface support a clastic mantle of some form. The implication is again that surfaces adapt and adjust to perturbations in their environment rather than undergo a catastrophic nature of change. The nature of variation identified in this thesis supports this suggestion.

With these parallels, SOS presents an attractive model on which to base an understanding of the slopes of the Badia. Process action in the Badia in virtually impossible to understand at the temporal scales involved to witness significant degrees of surface modification. The control over the simple rules that dictate the action and interaction of the system components can potentially be based on the findings made from the image analysis and surface hydrology experiments. Suitable tools are available, such as cellular automata, which have the ability to examine the nature of interactions and dynamics of such a system, under highly controlled modelling conditions.

6.5 Model design

Adopting a cellular automata modelling approach presents several advantages for the study of the dynamics and modification of the surfaces of the northeast Jordan Badia. Cellular automata are mathematical models of systems which are composed of many simple, individually acting parts, and are hence considered synergetic (Wolfram, 1984). A cellular automata is an array of discrete *automata*, or cells. Complex behaviour has been found to arise from the interaction of simple cells and as a result a cellular automata is considered to act as dynamic system (Bak, 1997). Cellular automata are considered totalistic. The state of a component within the array is derived as a product of the states of the neighboring components. Generic properties are commonly apparent as independent from the precise details of the cellular automata construction. The similarities between the behaviour of self-organizing systems and the fundamentals of cellular automata are numerous. Their multiple component composition and structure results in complexity, order and random forms, as is commonly witnessed in self-organizing systems. Cellular automata are adaptive to their conditions, changing behaviour and their final configuration in response to minor perturbations in interaction behaviour. Contrary to self-organization, cellular automata are well understood. Since their introduction in the late 1940s by von Nuemann (Tofolli, 1996), cellular automata have been widely applied (Wolfram, 1984). The attraction of highly simplistic rules applied to a random starting condition applied to many situations. A modelling approach using cellular automata allows precise controls over both the initial conditions, the interaction rules and is also capable of generating statistics with regards organization, optimization and pattern as the model evolves.

3.5.1 Construction of the cellular automata model

As part of this research cellular automata model was developed that was designed to simulate the surfaces of the northeastern Badia. The modelling approach is a preliminary attempt to simulate the processes in action on the Badia surfaces. The variation of the rules which dictate the behaviour of the model can be altered in accordance with the nature of surface variations observed in the field.

The model construction is based on a simplification of the northeastern Badia surfaces. The surfaces are reduced to a two dimensional surface, the plane of which lies parallel to the ground surface. The model surface is comprised of a matrix of clasts and sediment. The resulting binary image or matrix of square cells can have one of two states: clast or sediment. The surface is represented as a lattice or array, comprised of square cells. The matrix operates over a slope whereby objects can only move down-slope. Three clast sizes are used in the model, all of which are square cohesive blocks of cells. These are *small*, 1 cell width, *medium*, 2 cells wide and *large* clasts, 3 cells wide. Probability of movement of an individual clast is proportional to both the specific properties of the clasts and also those of its neighbours. The conditions form the basis of the rules which dictate the movement of clasts across the surface.

Clast interactions are dictated by a series of conditions or rules, all of which are pre-definable. The state of the rules remains consistent throughout the model simulation. The rule set was developed to be analogous to the processes dictating the potential iterative movement of surface clasts in the northeastern Badia observed in this study. Movement is restricted by friction between clasts (**f(clast)**). Friction acts horizontally across slope and also up-slope between diagonal cells. Clast size influences the probability of that clast moving (**p(clast)**), which again has a direct physical analogue. The sum of the probabilities of movement minus the frictions acting between the clasts (**p(move)**), dictates whether a clast will move (Table 2). The controls on model behaviour are considered as surrogate values for many of the variations which naturally occur in the field. In the model, eleven parameters of the surface and clast interactions can be controlled and varied (Table 6.1).

Variable name	Property		Range (probability)
Matsize	Width of the cellular automata array – the matrix is square		10 – 1000
Totcl	Total number of clasts which defines cover percentage when combined with Matsize		
small rocks	Defines clast size sorting. The number of large clasts is calculated when combined with Totcl		Matsize / 1
Medium rocks			Matsize / 4
IT_{max}	Number of iteration steps		10 – infinity
Sangle	Angle of slope – defined as a probability of movement between 0 and 1. A higher slope angle is described as a higher probability of movement		0 – 1
p(small)	Probability of clast moving p(clast)		0 – 1
p(medium)			0 – 1
p(large)			0 – 1
Diagonal friction (f_{diag})	Friction between two diagonal cells, up-slope	f(clast)	0 - 1
Double diagonal friction (Dfddiag)	Friction between a cell and two diagonal up-slope cells	f(clast)	0 - 1
Lateral friction (f_{la})	Friction across slope between two cells	f(clast)	0 – 1

p(move) = p(clast) – f(clast)

Table 6.1 Model parameters and variables

The variables outlined in Table 6.1 influence the nature and speed of interactions between clasts. The probabilities of clasts moving are determined by the condition of the neighbouring cells. The outcome of an interaction between occupied cells, or clasts, is totalistic, in that it is determined by the product of the frictions between clasts and the probabilities of each individual clast moving. All feasible arrangements and types of interaction are detailed in Table 6.2.

Table 6.2 Clast interaction outcomes

where:

1 = cell occupied by clast

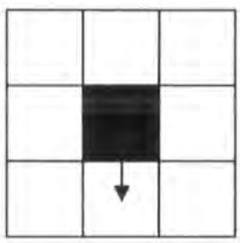
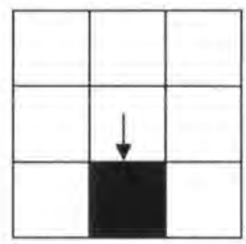
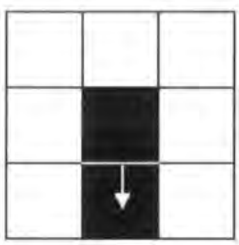
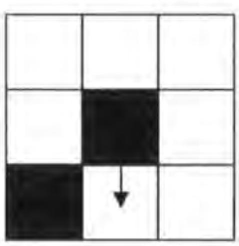
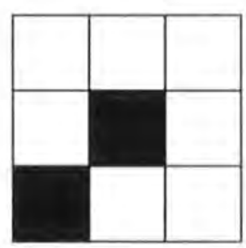
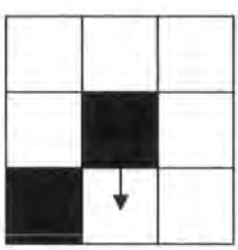
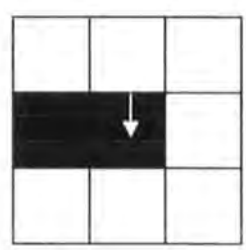
0 = cell empty

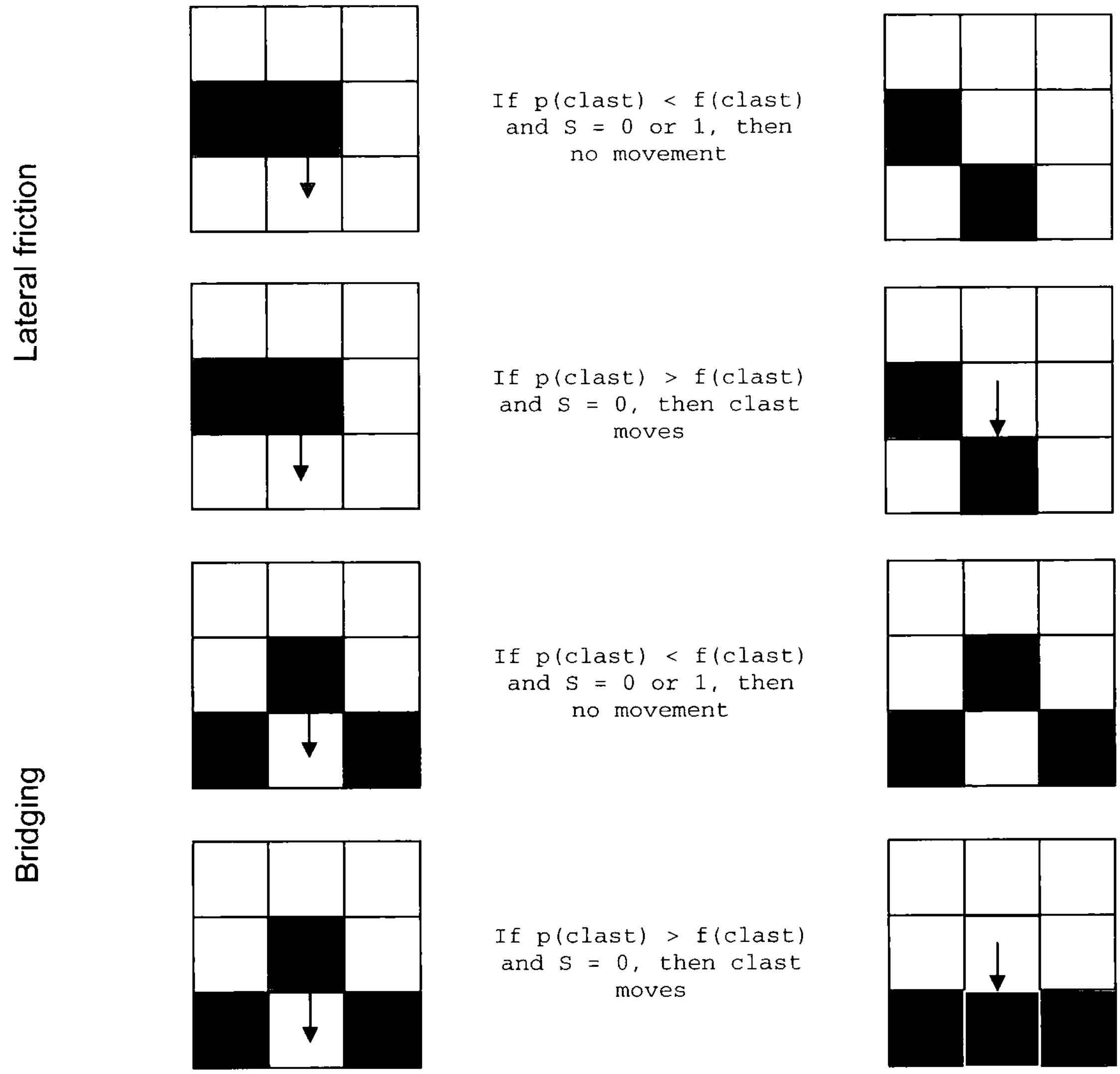
A clast movement is always by 1 cell only

There is no up-slope interaction between cells

p(move) = p(clast) – f(clast)

NW	N	NE
W	**C**	E
SW	S	SE

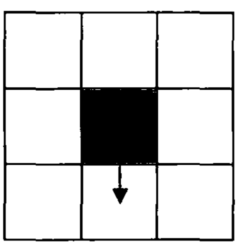
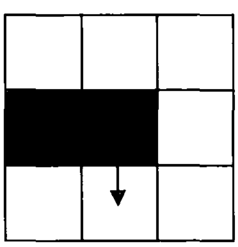
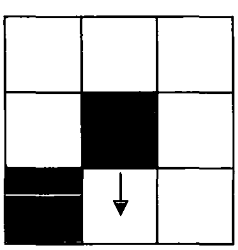
Situation	Before	Condition	After
Free movement		If p(clast) > f(clast) and S = 0, then clast moves	
Stacking		If p(clast) < f(clast) and S = 1, then no movement	
Diagonal friction		If p(clast) < f(clast) and S = 0 or 1, then no movement	
		If p(clast) > f(clast) and S = 0, then clast moves	

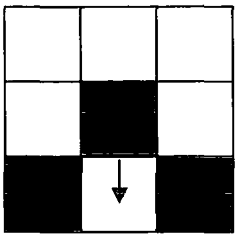
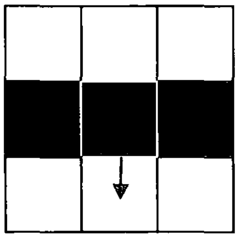


An example of the calculation of the probabilities of clast movement is given in Table 6.3.

Table 6.3 Example of run set-up conditions and outcomes

Parameter		Value (Run X in coefficient of variation tests)
Matsize		125
Totcl		1547
small rocks	CIS	773
Medium rocks	CIS	516
IT_{max}		4000
Sangle		0.5
p(small)	p(clast)	0.5
p(medium)	p(clast)	0.25
p(large)	p(clast)	0.125
Diagonal friction (f_{diag})	f(clast)	0.25
Double diagonal friction (Dfddiag)	f(clast)	0.125
Lateral friction (f_{la})	f(clast)	0.25

Situation	Summary of situation	Probability of Lock
	= p(small) x Sangle	p(move) = 0.25
	= p(small) x f_{lat} x Sangle	p(move) = 0.0625
	= p(small) x f_{diag} x Sangle	p(move) = 0.0.625

	= p(small) x Dfddiag x Sangle	p(move) = 0.03125
	= p(small) x 2(f_{lat}) x Sangle	p(move) = 0.03125

The rules defined above result in the following model assumptions which should be borne in mind when considering the results and their implications for relating the model output to the northeastern Badia.

- Clasts do not *knock-on.* Collisions are elastic and momentum is not transferred. This is thought to be the most representative of the northeastern Badia. Movements are iterative and small scale, momentum transfer resulting in sequential movement of clasts is therefore limited.

- Clasts are not *deflected.* The nature of movement in the northeastern Badia is suggested to iterative and small scale. Deflection is more likely to occur in a system where the clasts have more significant velocities and momentum.

- Clasts cannot move around or *rotate* around other clasts. If an object is stationary, then clasts in the matrix column above can only stack up and not roll around the static clast.

- The underlying sediment surface is uniform in form and character. There is no consideration of microtopography and the sediment surface is assumed to have a uniform gradient.

- The initial distribution of clasts is randomly generated but a given cover percentage can be defined by specifying the number of clasts of various sizes on the surface.

3.5.2 Model output

Three outputs from the model were derived. First, images of each time iteration in the model were exported and saved. These are in the form of a binary data file that can be displayed as an image (.bmp) file. Various analyses can be undertaken on the image, including box fractal dimension to calculate the image form variation between model conditions. The second and third outputs from the model were measures of the model behaviour, Lock and Org, form the main quantitative output from the model.

- **Lock**

  Lock is the mean probability of all clasts in the matrix moving during the next iteration. It is calculated as the product of probability of the individual clasts moving and the frictions between neighbouring clasts, as defined above. Lock provides a measure of surface stability and describes the tendency of clasts to move.

- **Org**

  Org is the mean number of neighbouring cells which are occupied by other clasts, calculated for all clasts in the array after every iterative loop of the model. The mean is calculated from the cells directly above, below, left or right of the clast in question. The value of Org is therefore larger for larger clast sizes. Org provides a measure of the condition of neighbouring cells and is therefore a measure of surface structure, or organization.

Finally time or iterations are recorded incrementally, such that temporal changes in system dynamics can be assessed.

3.5.3 Model code and function

A flow diagram of model behaviour was developed prior to model construction (Table 6.4). The model begins by constructing a random distribution of clast cells within the matrix, to a size cover percentage and clast size distribution. The model then runs an iterative query loop which equates the probabilities of each clast moving. The loop results in either a down-slope movement or results in the clasts remaining fixed in position until the next iteration query loop. The calculation of probabilities is based entirely on the run-setup previously defined prior to the start of the model. The variables controlling all parameters of the experiment are held in an instruction file (rundata.txt). Model output is in the form of text files, which are batch processed using Visual Basic Macros embedded in the model, and output into Microsoft Excel. The speed of the model is dictated by both the number of clasts on the matrix, the size of the matrix and the processing speed of the computer.

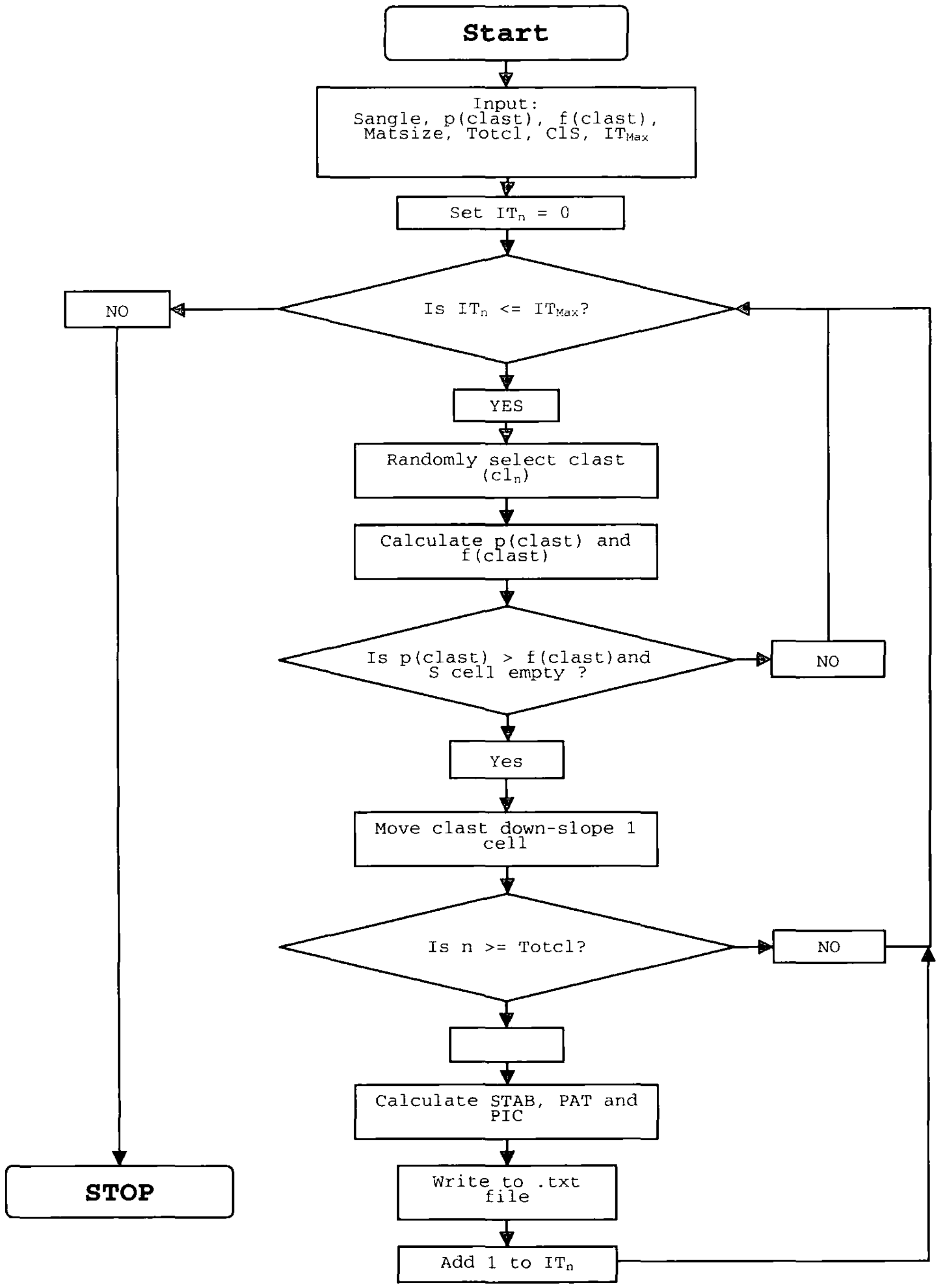


Table 6.4 Flow diagram of model operation

Sangle	=	Slope angle (fraction)	cl_n	=	Queried clast
p(clast)	=	Probability of clast moving, relative to size	ClS	=	Number of clasts in small and medium fraction*
f(clast)	=	Friction on each clast, due to Orghood conditions	IT_{max}	=	Total number of iterations
Matsize	=	Matrix width and length	IT_n	=	Present iteration
Totcl	=	Total number of clasts (all sizes)	* number of large clast = Totcl - ClS		

3.5.4 Model experimental set-up

The modelling procedure is based on a parametric study to understand the influence of each of the modelled variables on the behaviour of the interactions between particles and the resulting influence on the modelled surface character. The variables tested were selected to compliment the findings from the surface characterization and surface hydrology. Six variables have been selected to identify their role in controlling surface dynamics and form. These are percentage clast cover, clast shape, clast size sorting, slope angle, weighted means and finally a randomly generated set of model parameters. The first five variables have been shown previously to be significantly linked to slope form and process (Chapter 5). The nature of link is complex and varies considerably between locations. The model aims to assess each of the factors in controlled conditions. The 119 model experiments undertaken are split into 6 sets (Table 6.5).

Run set	Run numbers	Variables under test
1	1 – 30	Percentage cover
2	31 – 63	Friction angle
3	64 – 72	Clast sorting
4	73 – 102	Slope angle
5	103 – 114	Weighted means
6	115 – 119	Random probabilities

Table 6.5 Run set configurations

The variables under examination were incrementally increased in a series of model runs. The variables not under examination are maintained at constant values. The constants used for all experiments are detailed in Table 6.6. The values were selected after a series of trial experiments with the model.

Variable	Value
Matsize	125
Totcl	33 % cover
IT_{max}	4000
Sangle	0.5
p(small)	0.5
p(medium)	0.25
p(large)	0.125
f_{diag}	0.25
Dfddiag	0.125
F_{lat}	0.25

Table 6.6 Model variable constants

The behaviour of each experimental was quantitatively assessed using mathematical function. This function described the rates of change during the course of the simulation and assessed the final stable value of the system. The final state of the system was assessed using both Lock and Org. A quantitative comparison between model dynamics and final outcomes allowed the influence of each parameter to be directly compared. Additionally, the box fractal dimension of the final surface configuration is generated using the method used in the image analysis procedure, again allowing a quantitative comparison of model outputs between different run configurations. The benefit of this is that the results from the model can be directly compared to the results derived from the image analysis on the surface of the northeastern Badia.

The results of the modelling are presented in seven sections. Firstly general qualitative and quantitative observations of model behaviour are presented and then each of the six individual model set-ups and their results presented. Throughout links are made with geomorphological observations, similarities and parallels from the field.

6.6 General model observations

In all modelled conditions the rules imposed acted to modify the initially random configuration of the surface. In some runs the changes were only slight, whereas in others a distinct change in surface form was noted. Surfaces undergo a modification to a state which is non-random. The rate and magnitude of this departure away from the initially random conditions varied between run set-ups. Some models resulted in clusters of clasts. Others produced linear features both, with against and at constant angles to the contour of the slope. Evidence of queuing or stacking whereby a static clast holds up up-slope clasts was seen. Under high frictions, clasts were seen to stick or lock together forming initially small clusters which later agglomerate into larger concentrations. Clusters are frequently centred on a core stone often of a larger size (Plate 6.2).

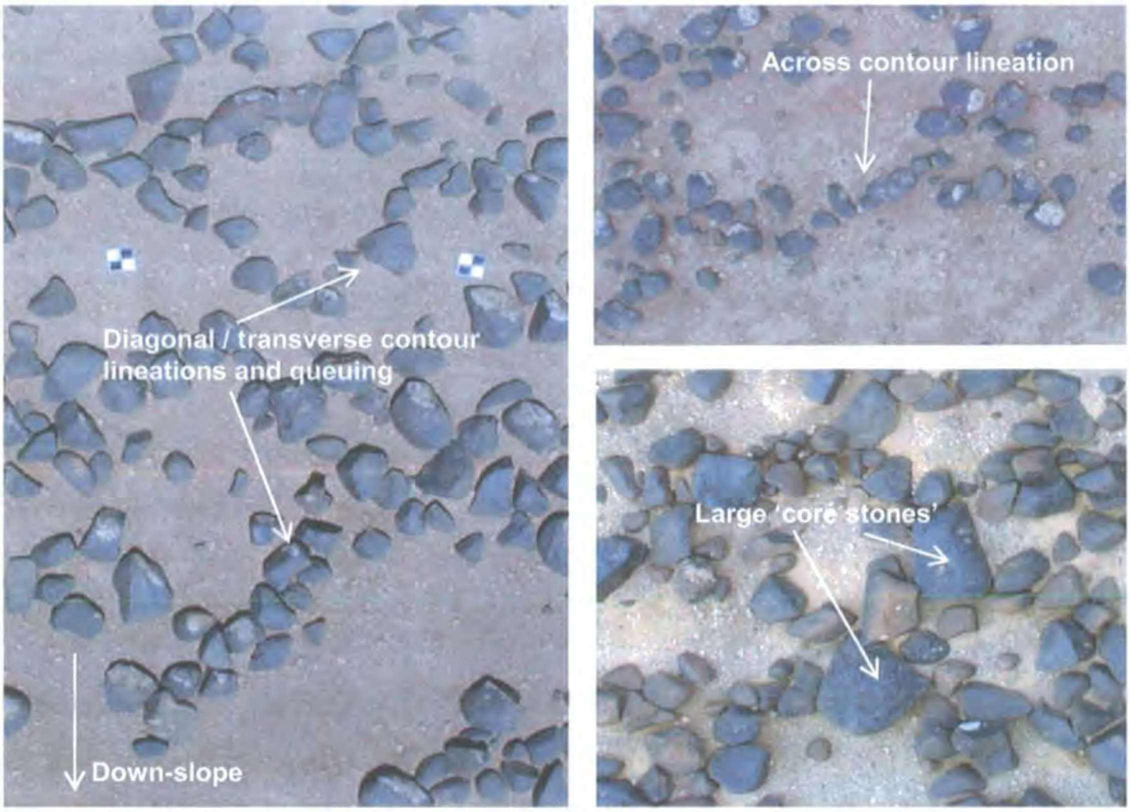


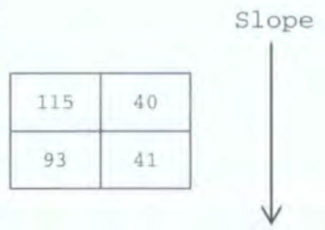
Plate 6.2 Examples of clast surface structures in the northeastern Badia (all images oriented down-slope)

Relatively few of the run set-ups resulted in a totally locked or static arrangement after 4000 iterations, but rather maintained a stable asymptotic level of clast movements. Runs with medium or large clasts tended to produce more clearly defined structure, a result of the increased product of multiple frictions around the larger clast perimeters in addition to the visual effect of greater spaces between the concentrations of clasts. Linear increases in independent variables often resulted in complex and non-linear responses in either or both Org and Lock. Although distinct polygon networks were not formed, areas devoid of clasts and linear structures in the clast arrangement are clearly visible.

Four examples of model output are given in Figure 6.1. The model outputs are all at the same scale. Run 40 shows an incidence of clustering of small clasts with distinct areas showing a lower concentration of clasts. Run 115 shows an effectively random distribution which is not dissimilar for the initial starting conditions. This run was taken from the series of experiments with randomly generated probabilities of movements and frictions. Run 93 shows a surface comprised of the largest clast size, with clear evidence of queuing and lineation, and Run 41 shows a clear dendritic structure with lineations of both clast structures and corresponding linear areas devoid of clasts. In the majority of experiments the degree of structure or pattern increases. Movement decreases, hence the surfaces become more stable.

Run configurations

Run	40	41	93	115
total rocks	5156	5156	573	5156
small rocks	5156	5156	0	5156
medium rocks	0.5	0	0	0
slope	0.5	0.5	1	0.704378
p(s)	0.5	0.5	0.5	0.733637
p(m)	0.25	0.25	0.25	0.076259
p(l)	0.125	0.125	0.125	0.509067
Single diagonal	0.909	1	0.25	0.756016
Double diagonal	0.455	0.5	0.125	0.378008
Friction	0.123	0	0.25	0.736194



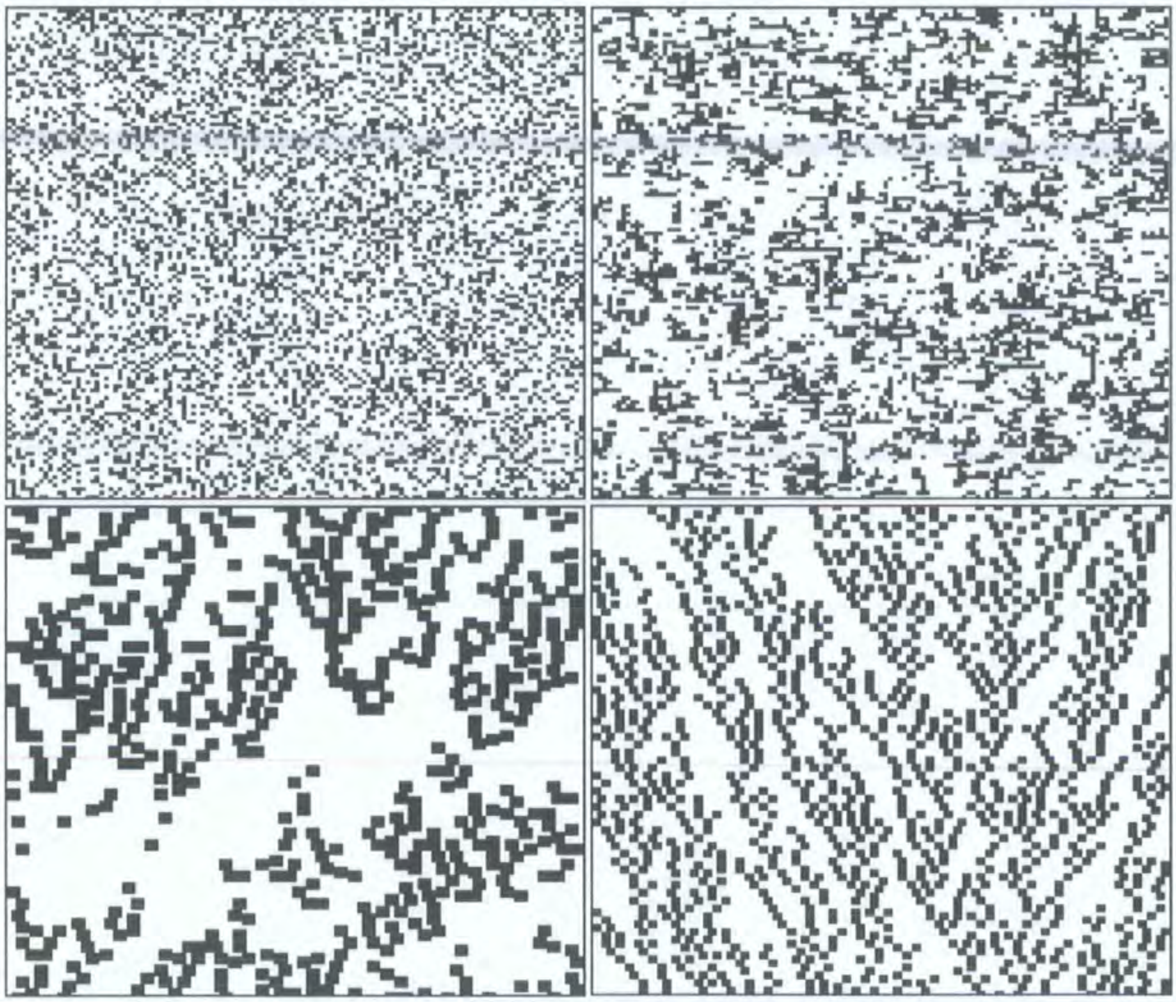


Figure 6.1 Example model outputs: runs 40, 41, 93 and 115

Both measures of Org and Lock change through the course experiment. In all experiments there is a significant degree of variation in both measures of behaviour, indicating a non static stable state. A typical example is given in Figure 6.2.

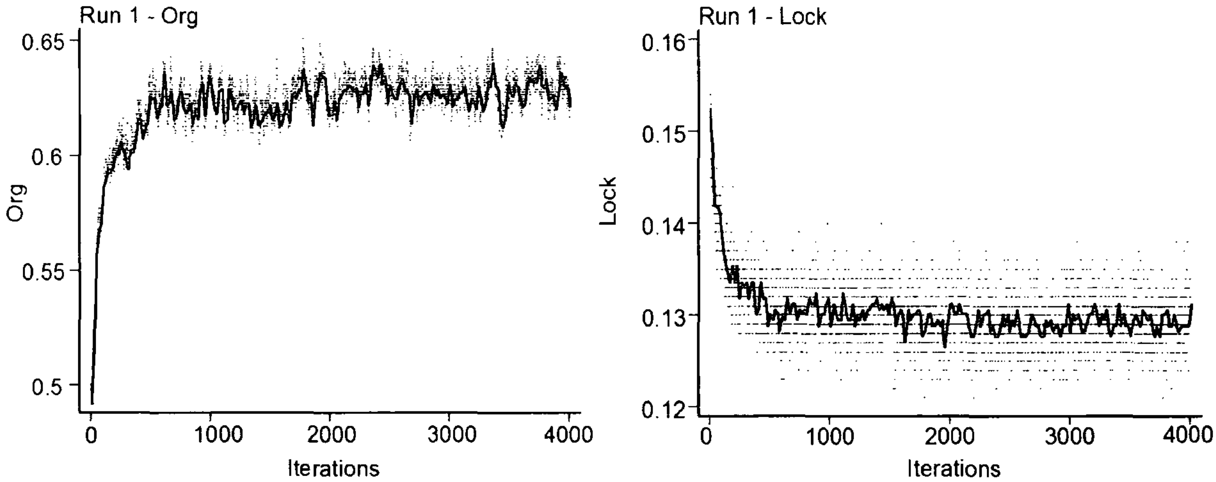


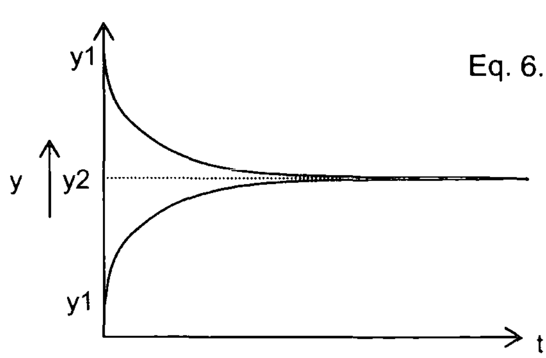
Figure 6.2 Run 1 - Org and Lock, median values connected by a cubic spline

Figure 6.2 shows the nature of the behaviour of the surface through the period of the model experiment. The initial condition is rapidly adjusted within the first 1000 iterations after which an asymptotic value of both Org and Lock is reached. Minor perturbations are apparent, suggesting that the surface is not static but has obtained an equilibrium level of Lock and Org form. It is tempting to fit an exponential decay or growth model to this type of behaviour, as employed by Ahnert (1994), but this appears not to be appropriate. An exponential decay or growth does not tend to an asymptotic value which is clearly apparent here. Decay in the case of Lock, or growth in the case of Org is initially exponential but the final state of the surface after 4000 iterations cannot adequately be explained by an exponential curve. Additionally, to solve an exponential decay curve, time or model iterations must be logged. Log time is conceptually tenuous as there is no physical analogue or explanation for the logarithm of time. A curve of the form shown in Equation 6.1 was therefore adopted.

$$y = y_1 \exp(-kt) + y_2(1 - \exp(-kt)) \qquad \text{Eq. 6.1}$$

where :

y	= Org (Lock) at t
t	= Iteration
$y1$	= Initial (Org, Lock)
$y2$	= Final (Org, Lock)
k	= Rate of change



The model, referred to below as Expapp, approximates an exponential approach to an asymptotic equilibrium value for both Org and Lock and a linear temporal scale can be used to solve the equation. The model works as both a growth and decay curve simultaneously. The model provides a measure of both the rate at which the surface reaches an equilibrium level (k), the value of the final asymptotic value (y2) and an approximation of the initial condition (y1). Figure 6.3 shows the Expapp model (solid line) fitted to measures of Org and Lock for Run 1, in addition to a standard exponential decay and growth curve (dashed lines).

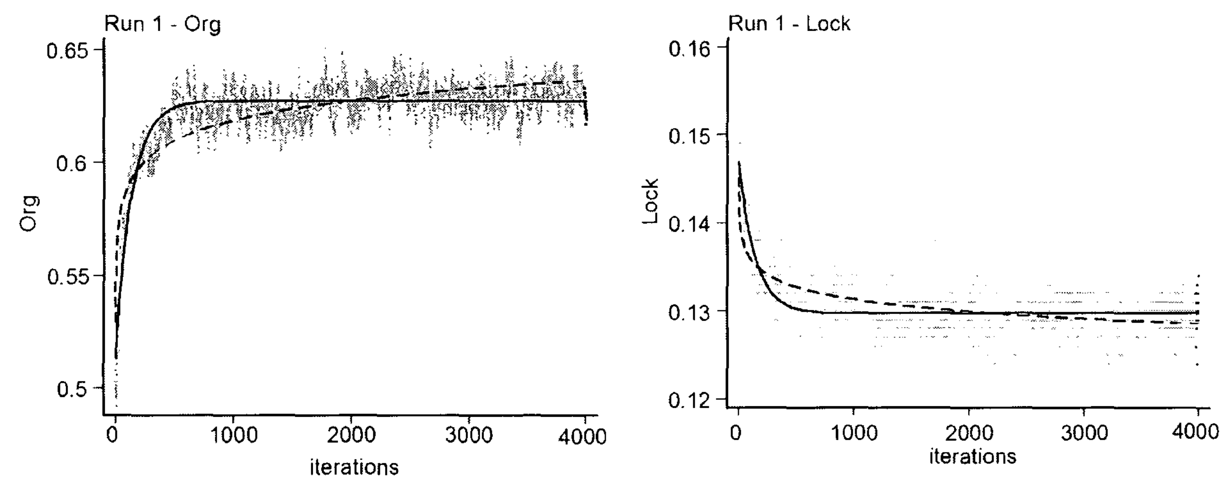


Figure 6.3 Expapp model (solid line) and standard exponential model (dashed line) applied to Run 1

Root mean squared error (RMSE) indicates the success of the Expapp in fitting to the derived values of Lock and Org. The smaller the RMSE the better the regression predicts the model output data. For Org in Run 1 RMSE for the standard exponential growth is 0.017, compared to 0.0078 for the asymptotic Expapp model, and for the Lock measure, the values of RMSE are 0.021 and 0.0027, respectively. The standard exponential curve underestimates the rate of change during the initial period of the experiment and later overestimates the value of the asymptotic final state of the system. The asymptotic model is logically and statistically more appropriate and significant. Expapp is used in the analysis below as a quantitative comparison between model outputs. The model is applied to mean data from 10 repetitions of each experimental run described.

Each model generates a binary image files. Box fractal dimension analysis was undertaken on each image for all 119 experiments. The initially random state generated a mean box fractal dimension of 1.897 (σ = 0.08), with 107 out of 119 experiments generating a lower box fractal dimension, suggesting a tendency, albeit slight in many instances, to non-random distributions. Figure 6.4 shows the distribution of box fractal dimensions generated, here represented as a kernel density estimate. The mean value for all experiments (1.794) and the mean value for the fractal dimension of the initial starting conditions (1.897) are indicated in the distribution. The bimodal distribution is explained as a function of the nature of the run set ups used and should not be considered as a characteristic of actual distribution of fractal dimensions for the entire model state space. The tail on the distribution indicates that under some, albeit infrequent circumstances a highly significant departure away from the random starting condition is apparent. The conditions which instigate the largest departures away from CSR are explored further below.

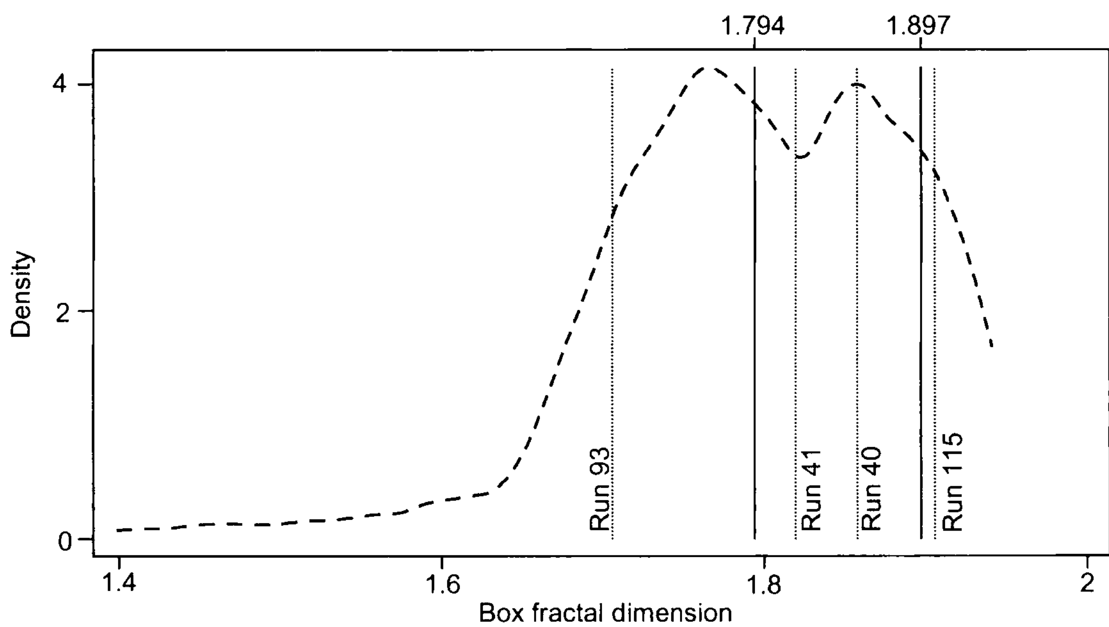


Figure 6.4 Kernel density estimate of box fractal dimensions for all runs, showing mean and initial condition and box fractal dimensions for the 4 example model outputs

6.7 Quantitative model analysis

3.7.1 Run set 1 –The influence of cover percentage

Ground surface cover percentage is commonly cited as a control on surface hydrology (Poesen *et al.*, 1994). The result presented in Chapter 5 demonstrates subtle links between ground cover percentage and the action of hydrological processes. The linkage is complex and appears intimately related to other variables of slope and surface character. Linear regression analysis is limited as a tool to explain the role of surface form on dictating process action. A series of experimental designs was developed to examine the influence of a linear incremental increase in percentage ground cover on surface form and behaviour. Table 6.7 gives the run specifications. The three clast sizes were tested separately for simplicity. Each successive run in this set experienced an incremental increase of 3.2% ground cover between 12.8% and 41.6%. Each incremental increase in ground cover was performed on surfaces with clast population composed of entirely, small, then medium and finally large clasts. Trial models identified that values around 33% demonstrated the most interesting behaviour. Above the experimental range defined the spaces between clasts was not great enough to permit sufficient movement to allow structure formation. Below, the gaps were such that reduced interactions between clasts meant that locking structures did not tend to form. As with all experimental run-sets, the variables not under examination are held constant (Table 6.7).

Run set	Percentage cover (small clasts only)			Percentage cover (medium clasts only)			Percentage cover (large clasts only)		
Run number		1 to 10			11 to 20			21 to 30	
		For intermediate runs			For intermediate runs			For intermediate runs	
Matsize	125	125	125	125	125	125	125	125	125
Totcl	2000 (12.8 %)	2000 - 500[a] (3.2 %) - 6500	6500 (41.6 %)	500 (12.8 %)	500 – 125[a] (3.2 %) - 1625	1625 (41.6%)	222 (12.8 %)	222 - 56[a] (3.2 %) - 722	722 (41.6 %)
Small rocks	2000	2000 - (500)[a] – 6500	6500	0	0	0	0	0	0
Medium rocks	0	0	0	500	500 – (125)[a] – 1625	1625	0	0	0
IT_{max}	4000	4000	4000	4000	4000	4000	4000	4000	4000
Sangle	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
p(small)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
p(medium)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
p(large)	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
f_{diag}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Dfddiag	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
F_{lat}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Repetitions		10 per rule set			10 per rule set			10 per rule set	

[a] Iterative increase between runs

Table 6.7 Set 1 - Run configuration

i. Stability

The final state of surface stability is shown to be dependant on the ground surface cover percentage. Additionally, under these conditions the clast size influences the level of the final stable state of the surface. The response to a linear increase in cover percentage is a relatively linear decrease in the final mean probability of movement (Lock) on the surfaces for each clast size (Figure 6.5).

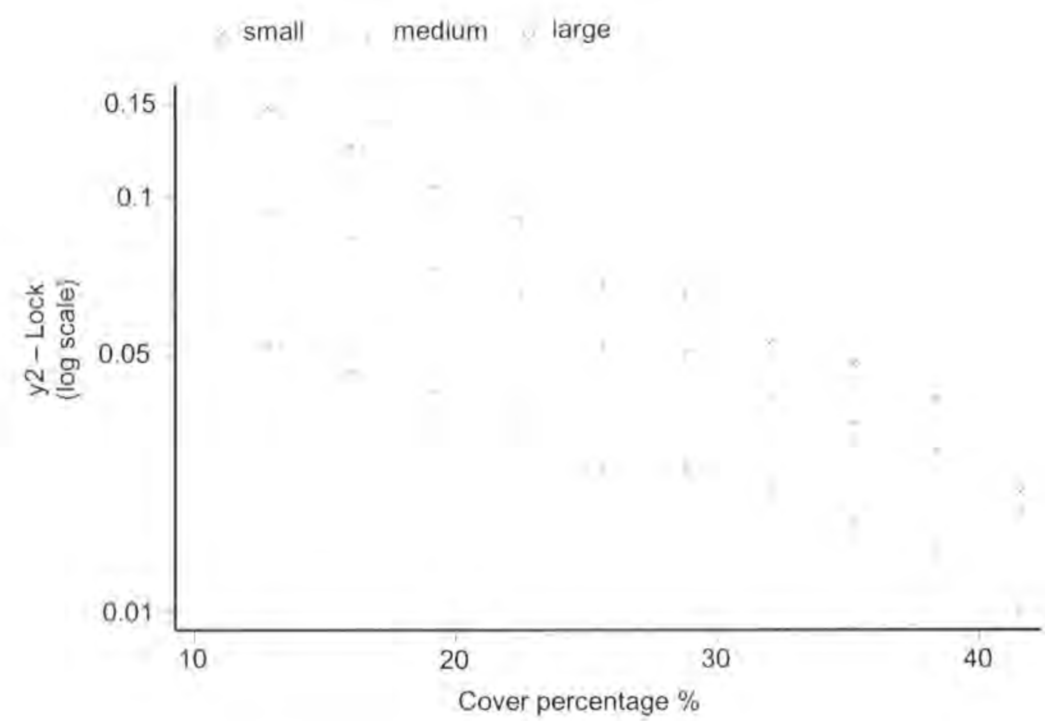


Figure 6.5 The variation of y2 – Lock, for runs 1 – 30, with cover percentage and clast size

The rate of change to reach an asymptotic equilibrium of probability of k-Lock also varies with cover percentage. Figure 6.6 shows that as cover percentage increases the speed with which the surfaces stabilize increases accordingly. Additionally, smaller clasts appear to stabilize more rapidly than larger clasts, probably as a result of their greater likelihood of movement. The behaviour of the model appears to be logical, as the higher the percentage cover then the less distance a clast has to move on average to come into contact with other clasts and lock into a structure. Figure 6.6 also illustrates the increased nature of variability of surfaces dominated by small clasts. Combined with the results in Figure 6.5, several key differences between these surfaces can be made. Even though all of the surfaces in the experiment use uniform clast sizes, the nature of the interactions is quite different. Larger clasts have a greater edge length available for interactions to occur. Total friction can be the product lateral, diagonal and double diagonal frictions simultaneously. The result of this is a potentially much lower probability of clast movement for larger clasts, as shown in Figure 6.5. As on smaller clasts, edge length is only one unit grid space width, on a surface with only small clasts the total friction between two particles can only ever be the product of either lateral or diagonal contact, apart from the exception of double diagonal friction, which within this model is deliberately considered separately.

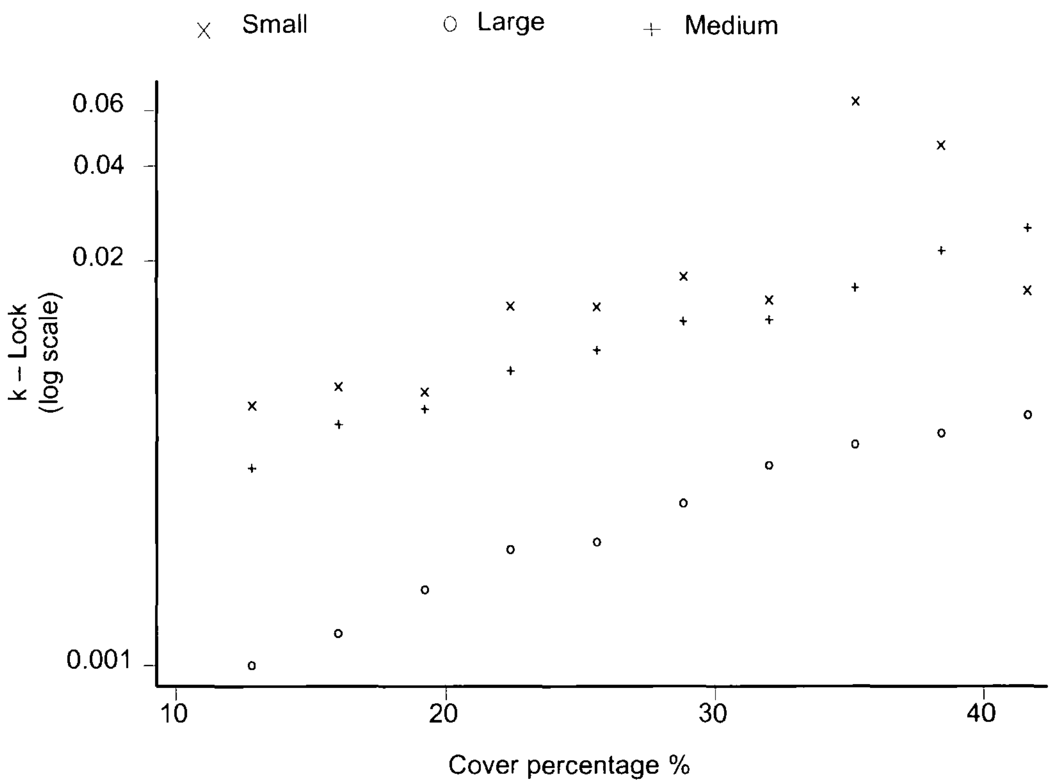


Figure 6.6 Variation of k – Lock, with clast size and cover percentage

A physical analogy to this in the field can be suggested. The model suggests that increased edge length on a surface with larger clasts may behave differently to that on a surface with small clasts due to an increase in the number of interactions, and have a resulting influence on the spatial character of the surface. On a small clast dominated surface the friction forces on and between clasts is low due to short edge lengths. The magnitude of the frictions between clasts in this fraction is closer to the magnitude of the force of the clast movement mechanism. Small clast movement is controlled by frictions of values closer to that of the forcing mechanism than those acting on and between larger clasts. Smaller clast dominated surfaces may therefore be expected to behave more sporadically and respond to events of a lower magnitude than larger clast dominated surfaces. Surface pattern may form but accordingly may breakdown, whereas greater total distances of movement maybe expected on surfaces with larger clasts. The implication of this size control on structure is that pattern may be scale specific. The behaviour seen in the model may explain the presence and absence of pattern in some areas, particularly between basalt types.

i. Organization

Pattern measured by the mean number of occupied neighbourhood cells (Org), increases with ground cover percentage for small and medium sized clasts (Figure 6.7), but appears to have little influence on large clasts dominated surfaces.

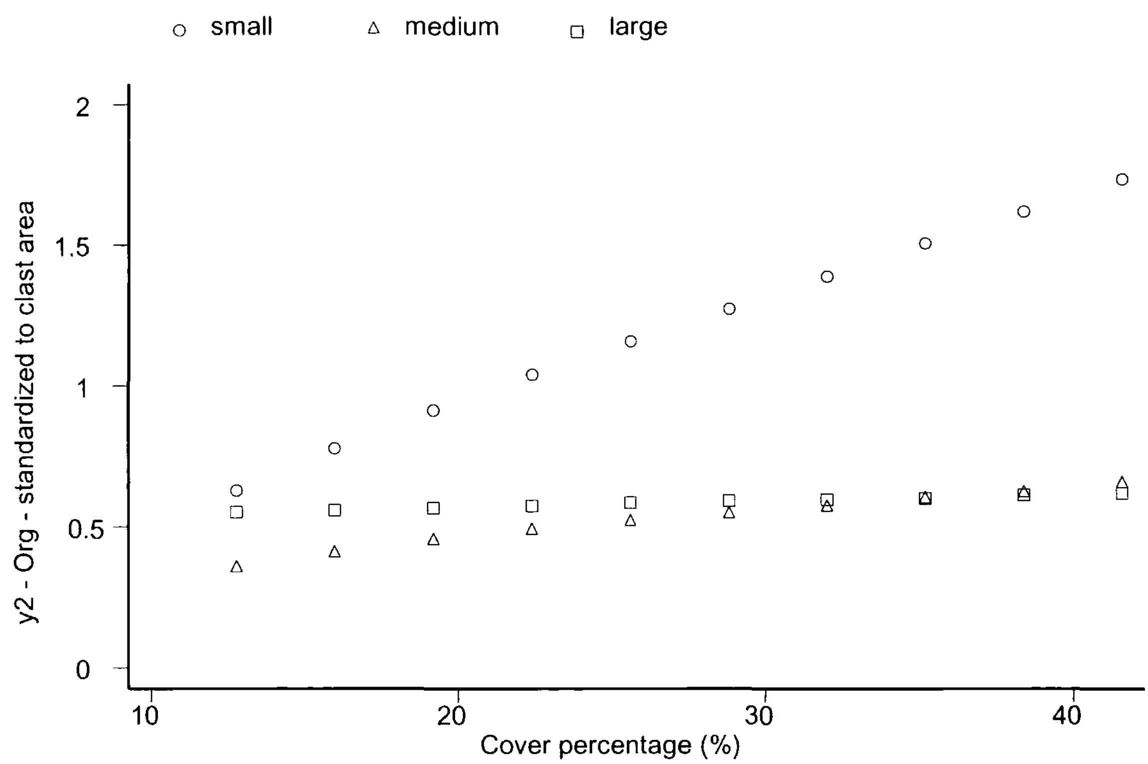


Figure 6.7 Variation of Org with cover percentage, as influenced by clast size

The increase in Org with cover percentage appears highly linear; r^2 values for linear least squares regression between percentage cover and y2-Org are 0.998, 0.983 and 0.994 for small, medium and large clast dominated surfaces, respectively. The nature of surface organization and its variation with the increase in cover percentage varies significantly between clast sizes. Small clasts show an increase in the tendency to organize with increased percentage cover, medium clast size dominated surfaces show a less pronounced increase and large clast show no discernable variation with increased percentage cover. Absolute values of Org appear to be strongly linked to clast size but the relative change in Org with cover percentage is linear. The result has an important implication for the surfaces of the northeastern Badia. The suggestion raised is that the larger the clast, the less likely the occurrence of structure. An increase in clast size increases the complexity of the interactions between clasts. In the northeastern Badia clasts are commonly mixed, which results in complex multiple interactions between several clasts. The large clast surfaces and their increased complexity are perhaps more appropriate as a model of the surfaces of the northeastern Badia. The limited variation in patterning with cover percentage on the more complex surfaces tested here is reflected in the northeastern Badia. No clear relationship has been found between cover percentage and any of the spatial measures of surface form developed previously. In the case of the small clasts dominated surfaces, which demonstrate a clear link between cover percentage and degree of surface organization, a much more simplistic nature of surface dynamics is apparent. The implication in the northeastern Badia is not dependent on clast size but rather on the complexity of the interactions between clasts. For example, on a surface with a tightly constrained unimodal distribution of clast sizes interactions may be simple, as the similarity in edge lengths of all clasts limited the number of clasts that can interact at one time. Clast interaction complexity is a function of clast size, clast size distribution and clast form and texture. Very subtle variations in any of these factors may have a profound influence of the spatial arrangement of the surface form.

Surface organization is also assessed using the box fractal dimension (Figure 6.8). A distinctly non-linear response in fractal dimension to an increased cover percentage is apparent. Increased cover percentage increases the dimensionality of the surface. Clast size also increases the degree of self similarity which can logically be explained by the formation of more complex structures at the scale of the 125 matrix by smaller clasts. The non-linear variation in box fractal dimension is surprising and appears contrary to the Org results above. Fractal dimension assesses the self-similarity of the resultant image. A higher percentage cover results in more clasts on the surface, which is more complex. It is also influenced by the spatial arrangement of clasts, irrespective of percentage cover. It would appear that spatial organization increases with percentage cover, but in a non linear manner. An examination of the resultant images for runs 21 – 30 (medium clasts) (Figure 6.1). Expapp curves were fitted to the increase in box fractal dimension with increased ground cover percentage. Optimum root mean squared error was found for a final box dimension (y2) of 2, and an initial percentage cover equal to zero, therefore the model results appear to generate a logical type of surface behaviour; 100% surface cover, has a square form and a fractal dimension of 2, as generated by the model. Box fractal dimension therefore undergoes an exponential increase to an asymptotic state.

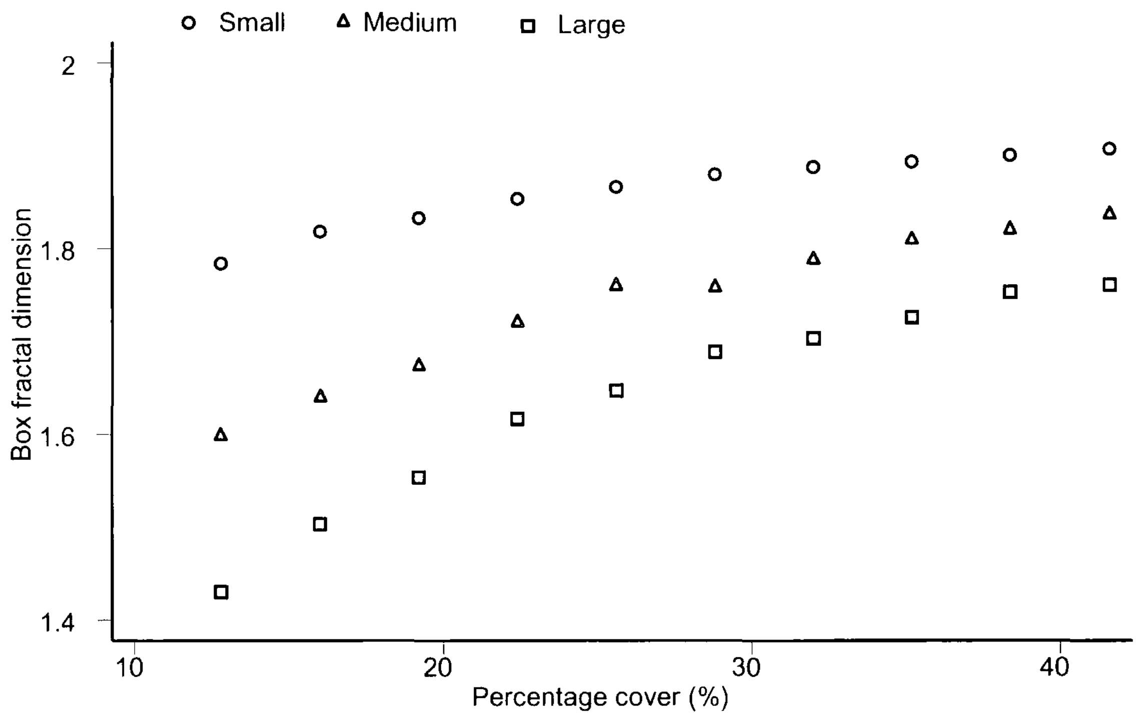
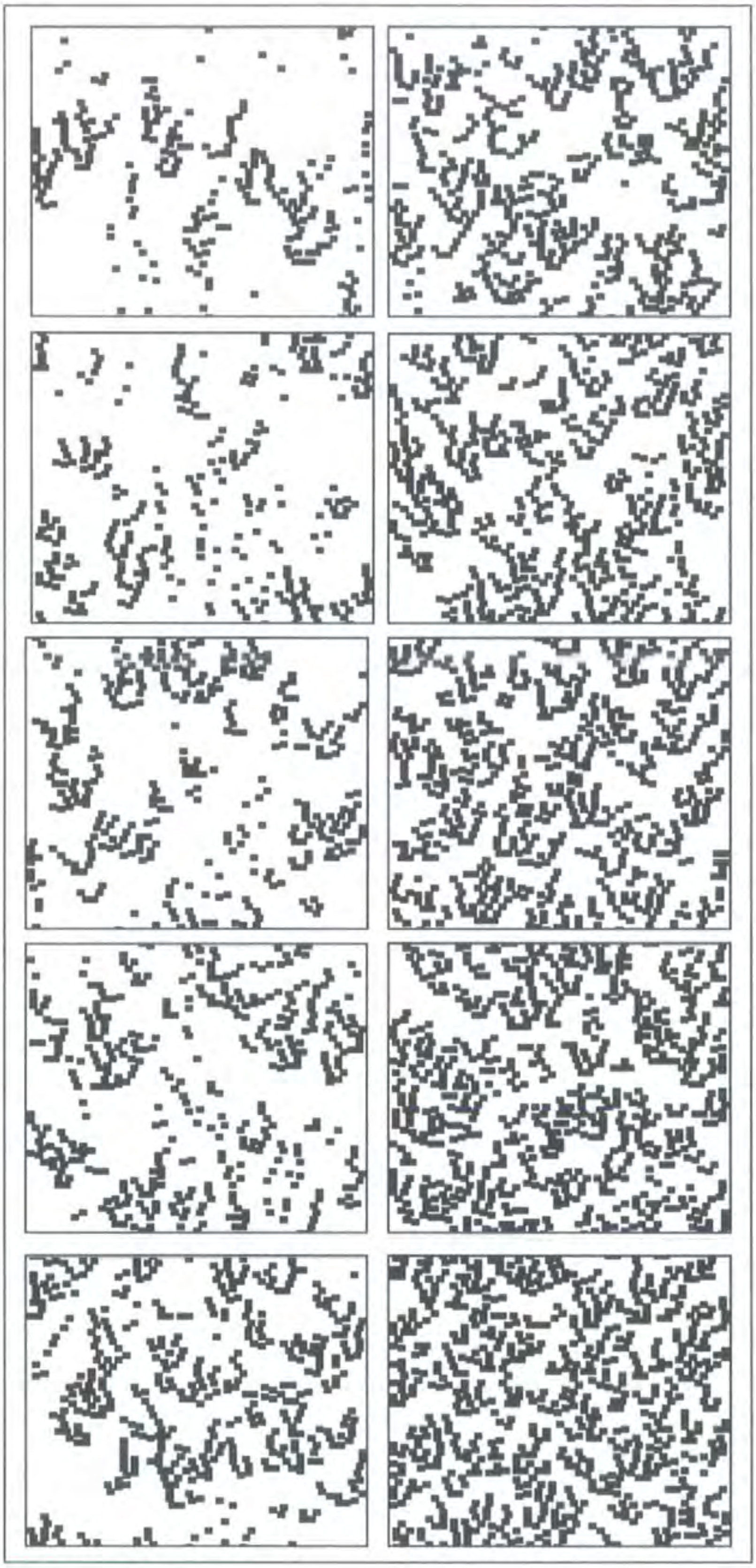


Figure 6.8 Box fractal dimension – set 1

Analysis of an incremental increase in percentage cover has suggested several interesting observations of surface behaviour. Increased percentage reduces the probability of clast movement in addition to increasing the speed at which the surface adjusts to an asymptotic equilibrium. Surfaces adapt to the local conditions and display a clast distribution which tends to a non-random form. Patterning or structure appears to increase with percentage cover under the conditions of simple clast interactions. It appears more likely however than on complex surfaces, where clast size, clast shape and texture are all highly variable, may result in an equally weak relationship between surface percentage cover and the occurrence of ground surface cover. The model output supports the suggestion raised from the image analysis of the surfaces which failed to generate statistically significant relationships between ground surface cover percentage and any measure of surface organization.



Run number	
21	26
22	27
23	28
24	29
25	30

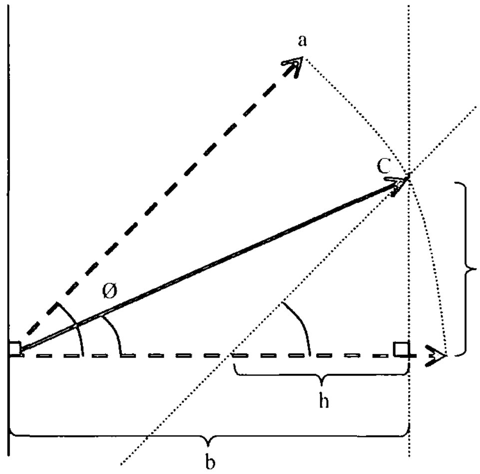
Figure 6.9 Model output images runs 21 – 30

3.7.2 Run set 2 - Influence of angle of friction

The image analysis of the northeastern Badia surface has revealed a distinct down-slope variation in particle texture and roundness. Modelling the influence of percentage cover has demonstrated the importance of clast interactions as a control on surface character, with an apparent control of size and edge length on the behaviour of the surfaces. Clast shape and texture have been identified as highly variable down-slope. The implication of this type of clast specific variation can now assessed in the model, by varying the resultant of friction forces between interacting clasts. By changing the friction and the angle in which its acts, a surrogate for clast texture and shape is simulated.

The model simulates inter-clastic frictions with two forces: one acting across the contour (f_{lat}) and one acting at 45^0 to the contour (f_{diag}). By altering the ratio of the two frictions the direction of the resultant averaged over the image, here termed the angle of friction, can be altered. This is designed to simulate the influence of clast rounding and surface texture, in addition to acting as a proxy for understanding the dynamics of variable clast interactions. The run set is designed to examine whether an optimum angle of friction exists under which surface structure is most likely to form and then assess the effect of this on surface dynamics. The direction and magnitude of the angle of friction in terms of a physical analogy to this in the northeastern Badia is difficult to judge. Friction and the potential of movement between real clasts is a result of a complex interplay of surface texture, contact length and size, clast inertia and the tendency of a clast to topple down-slope but it is suggested here that the influence of these interactions can be simplified to f_{lat} and f_{diag}.

A model was constructed whereby the magnitude of the resultant of f_{lat} and f_{diag} is always equal to 1. By altering the ratio between the two values, the angle of the resultant, termed the friction angle, is moved between 45° and 0° to the horizontal, in 5° increments with an additional experiment at the midpoint, at 22.5°. The respective values for f_{lat} and f_{diag} were calculated as shown in Figure 6.10.



$$h = C\sin\alpha$$
$$a = \sqrt{2}h$$
$$\therefore a = \sqrt{2}(C\sin\alpha)$$
$$b = C\cos\alpha - h$$
$$\therefore b = C(\cos\alpha - \sin\alpha)$$
$$\text{if } C = 1 \text{ and } Ø = 45^{\circ}$$
$$b = \cos\alpha - \sin\alpha$$
$$\&$$
$$a = \sqrt{2}(\sin\alpha)$$

C, resultant of a (f_{diag}) and b (f_{lat}) is always = 1

the angle of the resultant, varies between 45° and horizontal (0°) at 5° intervals

Figure 6.10 Calculation of friction angle

The resulting values of f_{lat} and f_{diag} are displayed with the other run set-up parameters employed in this series of experiments parameters are shown in Table 6.8.

Run set	Change in friction angle – cover percentage set at 33 % (small rocks only)										
Run number	31	32	33	34	35	36	37	38	39	40	41
Friction angle	0	5	10	15	20	22.5	25	30	35	40	45
Matsize	125	125	125	125	125	125	125	125	125	125	125
Totcl	5156	5156	5156	5156	5156	5156	5156	5156	5156	5156	5156
Small rocks	5156	5156	5156	5156	5156	5156	5156	5156	5156	5156	5156
Medium rocks	0	0	0	0	0	0	0	0	0	0	0
IT_{max}	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
Sangle	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
p(small)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
p(medium)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
p(large)	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
f_{diag}	0	0.123	0.246	0.366	0.484	0.541	0.598	0.707	0.811	0.909	1
Dfddiag	0	0.062	0.123	0.183	0.242	0.271	0.299	0.354	0.406	0.455	0.5
f_{lat}	1	0.909	0.811	0.707	0.598	0.541	0.484	0.366	0.246	0.123	0
Repetitions	10 per rule set										

- Values of friction here rounded to 3 d.p., but figures to 8 d.p. were used in the model
- Dfddiag is always held at ½ of f_{diag}

Table 6.8 Run configurations – Set 2

i. Stability

The influence of friction angle on surface movement is profound. Again three clast sizes were tested separately, each displaying a different nature of surface behaviour (Figure 6.11).

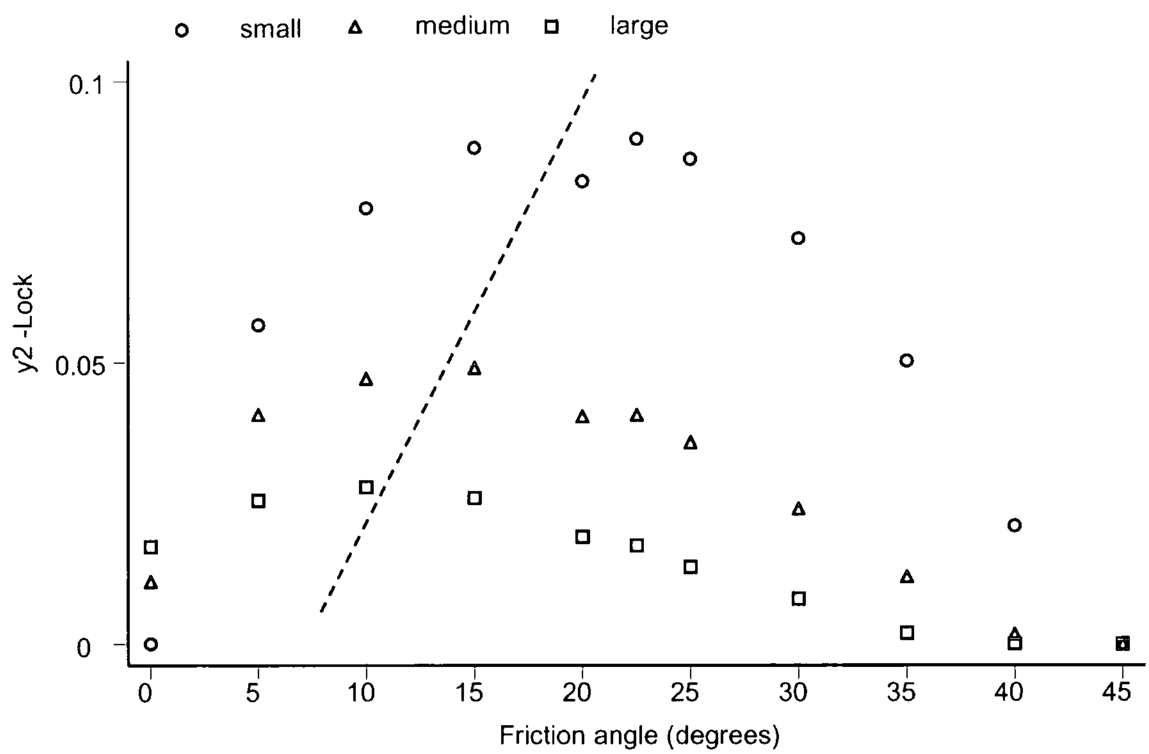


Figure 6.11 Influence of angle of friction on y2-Lock

Interestingly peak values of y2-Lock increase with clast size, indicated by the dashed line above. The small clast experiments generate a modal frequency distribution of y2-Lock, centred on a mean value of 22.5°, with the lowest levels of y2-Lock at 0° and 45°. The increase in y2-Lock with friction angle as dictated by clast size has several important implications. As clast size increases the edge length available for contacts and friction increases. The angle at which a clast can support another clast of equal or smaller size through friction is dependent on clast size. The geometry of an emergent pattern or polygon network is dependent on clast size, via the variable nature of friction contacts.

Despite altering the friction angle, the relative clast position in the matrix can only either be at 45° or 0° to the horizontal due to the grid layout. When the resultant is at 22.5°, neither f_{lat} or f_{diag} is dominant and correspondingly y2-Lock is large. The difference in behaviour between the three clasts sizes is also of interest. It is noticeable that medium and large clast sizes have a less dramatic response to a variable angle of friction. The tendency for the mean value of y2-Lock to move towards a friction angle of 0^{o} degrees with increasing clast size is a reflection of the changing ratio of f_{lat} to f_{diag} with increasing clast size (Figure 6.12). An analogy to this in the field can be made. Edge length increases geometrically with clast diameter. On a surface with larger clasts a greater contact edge length is available for generating frictions and contacts between clasts. Total friction between clasts increases as a result of both a greater length of clast contacts and a greater number of clasts in contact at one time. In addition to the increasing magnitude of friction the nature of the friction changes. With a greater edge length more clasts may come into contact. Larger clasts may have more than one point of contact, whereas smaller clasts may only be limited to one contact point. Edge lengths are of particular importance when considering the relative Lock of different size fractions on a surface with a mixed clast size distribution.

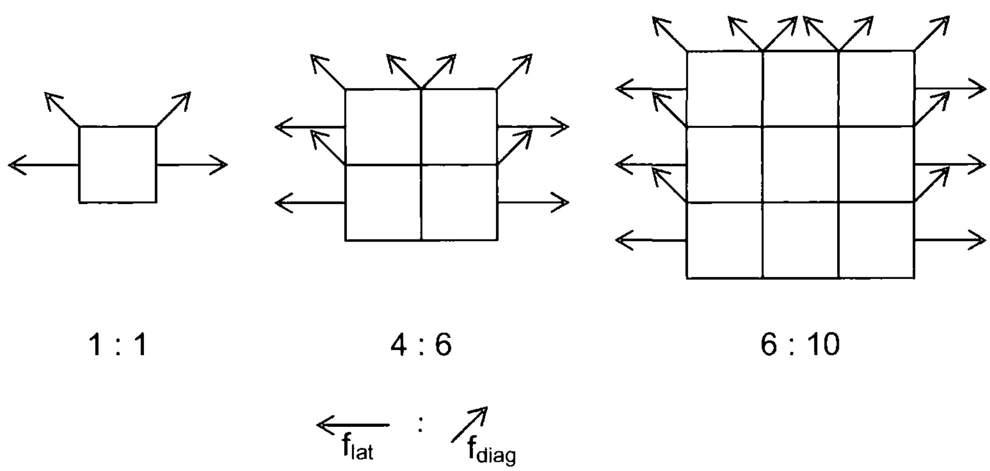


Figure 6.12 Changing ratio of friction forces with increased clast size

The rate of change to a stable state under various friction angles is complex. Figure 6.13 shows that clast size dictates the rate of stabilization of the surface. Small clasts tend to behave more erratically than medium and large clasts, reflecting the more muted response due to increased interaction complexity for the larger clast sizes. For small clasts, the rate of change to stabilization appears shows no significant decrease as the friction angle moves from 0^{o} to 45^{o}, whereas for medium and large clasts there is a clearly apparent decreases in the k-Lock, again a function of the changing nature of clast interactions with clast size. For large clasts the number and magnitude of f_{diag} relative to f_{lat} increases. As the angle of friction approaches f_{diag} (45^{o}) the probability of movement decreases and hence the rate of change to a stable state slows. Geomorphologically this suggests that large clast dominated surfaces maybe more resilient to modification and may take more iterative cycles to adjust to a change in forcing conditions.

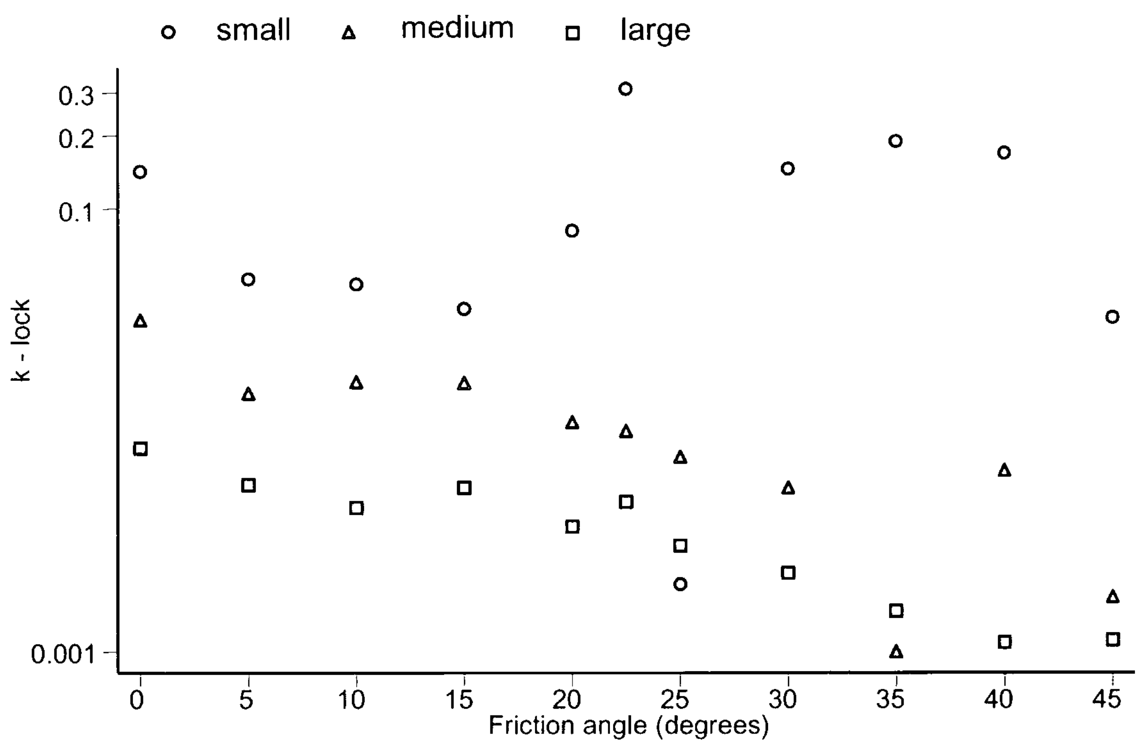


Figure 6.13 K values – rates of change to a stable state under variable friction angles.

ii. Organization

Angle of friction has a profound effect on the nature of pattern formation on the surfaces generated by the model (Figure 6.14).

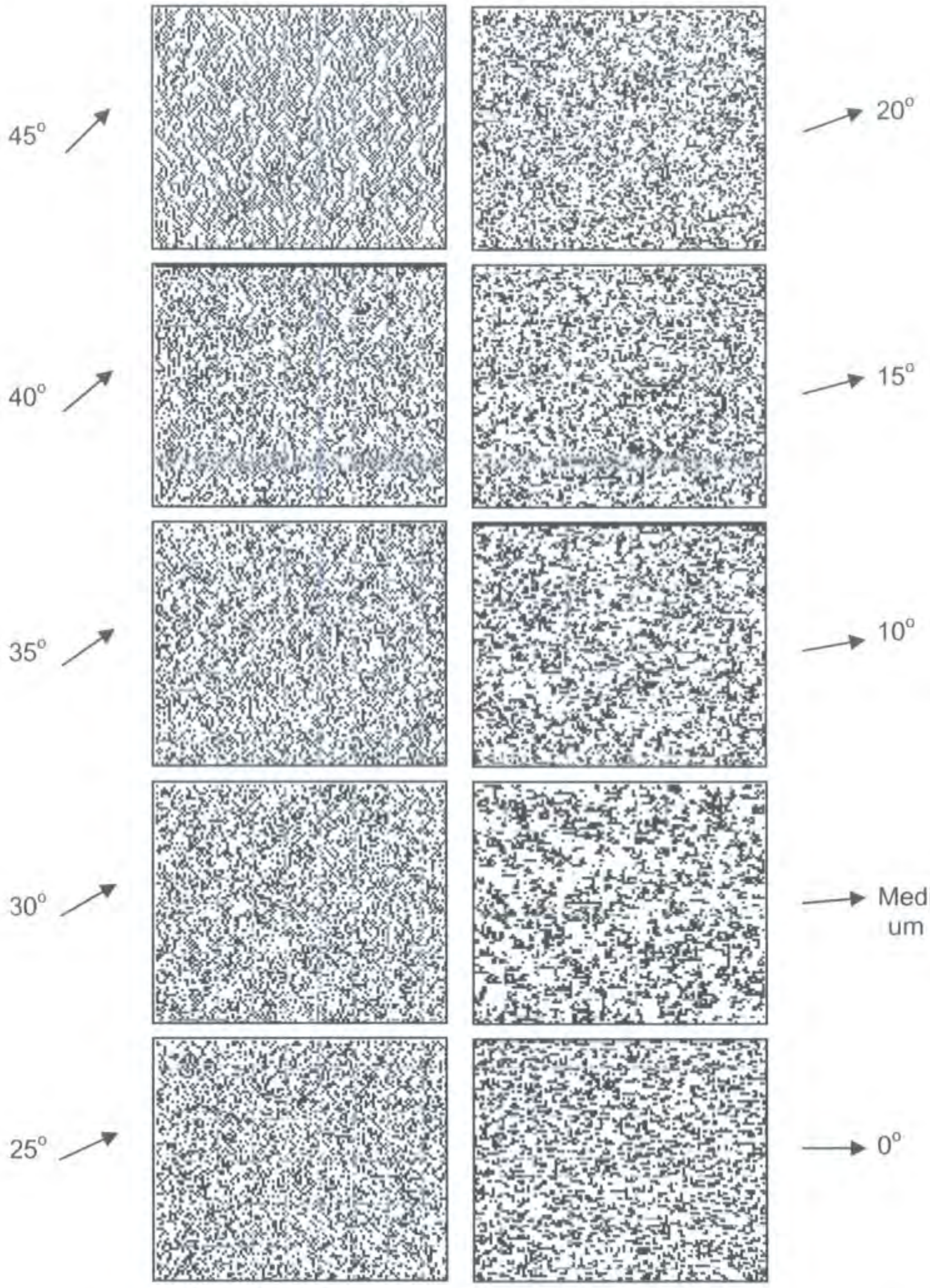


Figure 6.14 Runs 31 – 40 Variable angle of friction, indicated by the arrow for small clasts

Figure 6.14 shows the change in nature of structure with a varying angle of friction, the resultant indicated by the arrow for each image, for small clasts. The nature of pattern varies dramatically from a clearly dendritic surface pattern at 45°, to an apparently unordered structure between 20° and 25°, and then a clustered pattern arranged parallel to the contour with friction angle at 0° to the horizontal. Pattern measures corroborate the visual representation of spatial distribution of clasts seen above, as shown in Figure 6.15.

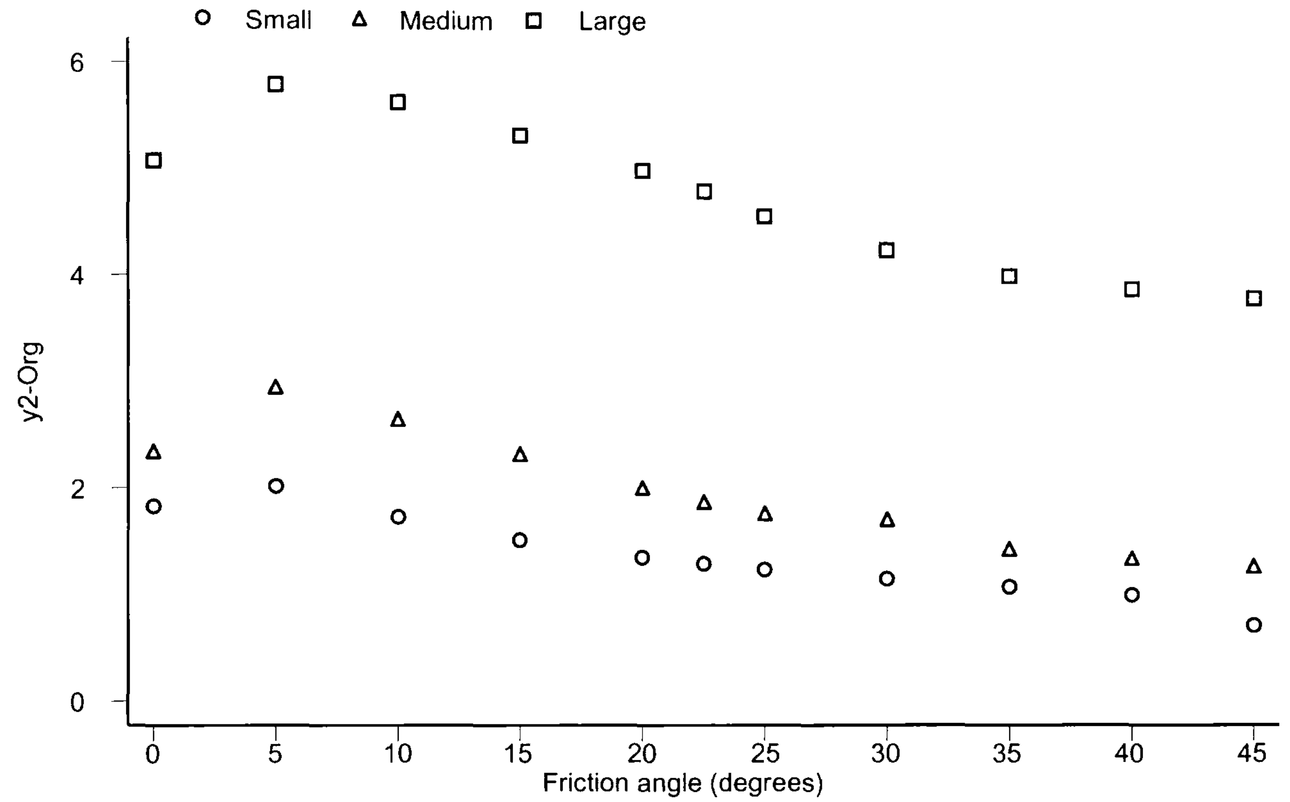


Figure 6.15 Run set 2 - The influence of friction angle on y2-Org

The three rocks sizes perform differently in the model. What is surprising is the maximum value of y2-Org for the 5 degree friction angles, for all three clast sizes, a distinction not seen in the y2-Lock. The maxima, seen in Figure 6.15, can be understood by referring back to the images in Figure 0.16. A friction angle of 5° appears to promote the greatest degree of clast clustering, even more so than 0°. At 45° the surface, although visually structured, is dominated by an almost uniform distribution of clasts across the matrix all held in position by the dominant f_{diag} and Dfddiag. y2-Org reflects an increase in clustering, the fractal dimension of the images reflects the degree of self similarity (Figure 0.18).

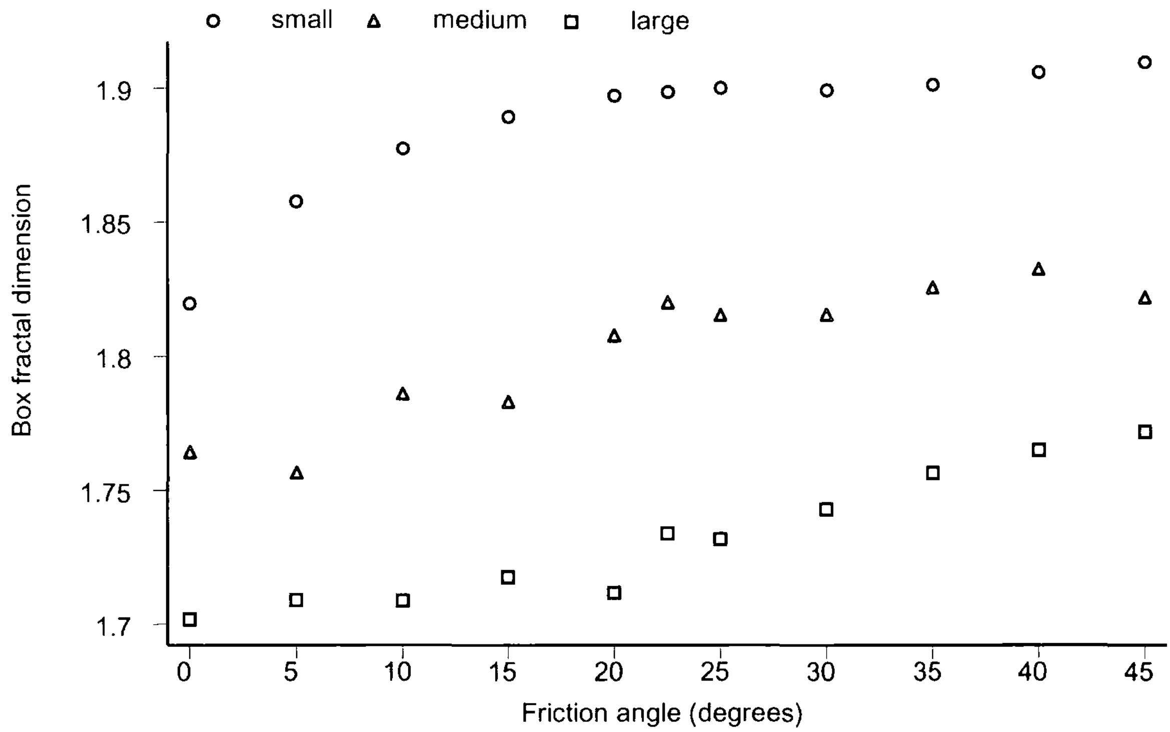


Figure 6.16 Box fractal dimension – Run set 2.

Figure 6.16 reflects the regularity of the structures seen in Figure 6.14, suggesting a higher degree of self similarity as the angle of friction increases to 45°. Again, the smaller clast dominated surface returns a higher box fractal dimension. All three clast sizes show a steady increase in image self-similarity with increasing angle of friction. Comparing y2-Org and box fractal dimension raises some interesting suggestions. y2-Org decreases with friction angle reflecting a higher degree of clustering as the angle tends to 0°. Clustering is not reflected in the box fractal dimension which rather reflects the degree of linearity and self similarity in the image. These observations can be extrapolated to the northeastern Badia. In the Badia structure is present, but on a visual basis, rarely continuous down a slope profile. The occurrence of pattern is unpredictable. It is often difficult to relate the presence and occurrence of structure to either surface or slope variables. Visually, pattern is either there or not. On a qualitative basis it is very difficult to suggest varying degrees of structure. A polygonal net appears as a polygonal net and there is qualitatively little transition between an ordered and random surface. Analysis of the fractal dimension at points down the surveyed slope profiles indicates a gradual change in the organization of the surface, which can be differentiated from other the influence of other surface variables. The image analysis and model pick out and quantify pattern and structure that the human eye is unable to see.

The model appears to replicate the conditions in the northeastern Badia. Run 31 shows a very clear dendritic style of structure which is easily recognisable as an organized pattern. Conversely Run 32, at least on a visual basis appears to show relatively little degree of organization, despite the run set-up being only slightly different from that in Run 31. The two statistics employed, Org and the box fractal dimension, indicate that there is a gradual transition from a random to a non-random distribution leading to an organized surface structure. The model suggests that subtle variations in the nature of interactions on the surface can have implications on the type and visual appearance of the surface structures. The implication is that what appears to be random in the field may well be at some transition between order and randomness.

The results from the spatial analysis of structure appear to be incongruous with those with regards surface stability. Measures of surface structure suggest that both clustered and ordered structures are stable, explained as a result of the increased number of contact points between clasts, which generates the lowest mean probabilities of clast Lock. The transition from clustering to linear structure shown is not reflected in a corresponding linear change in surface stability. As discussed, the most potentially unstable surfaces are those which are neither clustered nor structured.

Additionally it is notable that even those areas with Org exhibit some degree of dynamism. Surface structures are not static but dynamic. Structure, as an emergent property, is a manifestation of clast interactions and is not necessarily indicative of a static locked surface. If the controls on interactions change through time, for example increase clast rounding due to attrition or weathering, then the emergent surface structures may too reflect this. The model has shown that only a slight variation in the nature of clast interactions is needed to alter the surfaces both qualitatively and quantitatively. Given the apparent unstable nature of non clustered and non ordered surfaces, it is suggested that with external forcing held constant a surface will tend towards some form of organization. The development of Org reduces the entropy of the surfaces. A more mature surface should display greater degree of order.

In the Badia this is reflected in a greater degree of structure at the base of slope where process intensity is at its highest. Surfaces have experienced significant process action to modify their form to a more stable state, as indicated by Org. Again there are issues of homeostasis. When structure is present it may be self-perpetuating. As a locking structure develops its spatial extent and area increases, allowing more contacts with other clasts. This is potentially the reason that when a structure appears it is very clear, even though a transition in the degree of organization is rarely visually apparent. A lack of structures in the field can be suggested to be a reflection of either a location which does not experience processes of sufficient magnitude to modify the surface, or secondly, an area that has undergone some form of change in the controls on interactions. A surface under these conditions maybe in transition between a chaotic or random state to a more ordered surface organization.

Although the angle of friction does not have a direct physical analogy in the field, run set 2 has demonstrated the degree of sensitivity of the surfaces and the variability of emergent forms that result from only subtle variation in interaction properties. Features such as clast form may hold a significant control over the behaviour of the surface.

3.7.3 Run set 3 – The influence of clast sorting

Clast size has been shown above to play a critical role in the behaviour of the surfaces. The image analysis in the Badia has identified a systematic variation in the nature of clasts sorting by within and between locations and can be linked to surface, slope and hydrological variables with statistical significance. The following series of experiments aims to explore the role of various levels of clast sorting on the behaviour and dynamics of the surfaces. Again cover percentage is held at 33 %. Ratio of the clast size is kept at 1 : 2 : 3, as detailed in Table 6.9.

	Run number	64	65	66	67	68	69	70	71	72
		One clast size			Mixed clast sizes					
Clast size	Small	1	0	0	3	2	1	1	2	3
	Medium	0	1	0	2	3	3	2	1	1
	Large	0	0	1	1	1	2	3	3	2

Table 6.9 Proportional ratio of small : medium : large clast sizes – Runs 64 - 72

Every combination of small : medium : large in these ratios is tested in Runs 67 – 72. Runs 64 – 66 are undertaken for comparison between surfaces with one clast size and those with a mixture of clast sizes. Values of the coefficient of variation are calculated for each run set up using the formula described in Chapter 4, and is employed here as the measure of clast size distribution sorting.

Run set	Change in coefficient of variation – cover percentage held at 33 %, combinations of 3 : 2 : 1 ratio								
Run number	64	65	66	67	68	69	70	71	72
CV_b	0	0	0	0.861	0.697	0.579	0.528	0.663	0.611
		One clast size				Mixed clast sizes			
Matsize	125	125	125	125	125	125	125	125	125
Totcl	5156	1289	573	1547	1345	998	859	937	897
Small rocks	5156	0	0	773	448	166	143	312	224
Medium rocks	0	1289	0	516	673	499	286	156	224
IT_{max}	4000	4000	4000	4000	4000	4000	4000	4000	4000
Sangle	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
p(small)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
p(medium)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
p(large)	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
f_{diag}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Dfddiag	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
F_{lat}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Repetitions	10 per rule set								

Table 6.10 Proportional ratios of small : medium : large clasts, and run-set configurations - Runs 64 - 72

ii. Lock

The small number of experiments undertaken to examine the role of particle sorting in determining surface behaviour limits the statistical significance of the results generated, but nonetheless some tentative observations can be made. The final stability of the surfaces appears to be positively related to an increased level of clast sorting, though this relationship is not statistically significant (r^2 = 0.53, (for 5% significance, r^2 = 0.81)). A greater degree of locking between the surface clasts is achieved on surfaces with a more uniform distribution of clast sizes (Figure 6.17). There appears to be little or no relationship between the degree of clast sorting and the rate at which a surface stabilizes (Figure 6.17). Rates of change in surface character appear more complex.

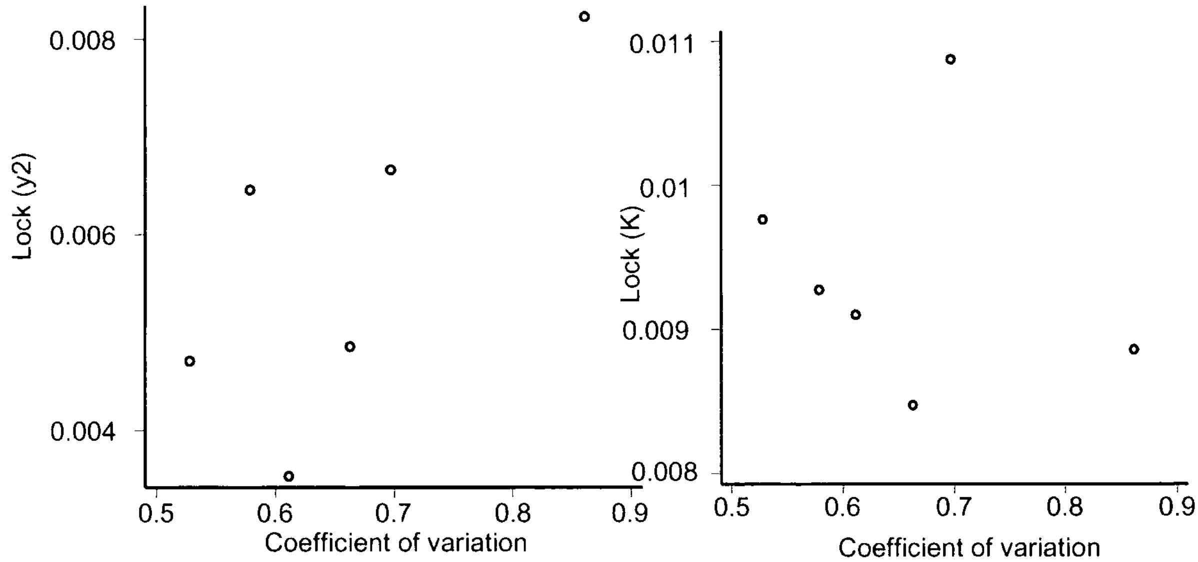


Figure 6.17 Variation of final stable state (y2-Lock) with coefficient of variation (left); Relationship between k-Lock and the coefficient of variation (right)

The Lock of clasts on a surface with a mixed clast size distribution is complicated by the interaction of objects that behave according to different rules, or probabilities of Lock. The relative importance of the individual size fractions in controlling in this instance the Lock of the surfaces is now addressed. The model output on surface with a mixed clast size distribution can be tailored to give details of the behaviour of each of the individual size fractions on the surfaces. Figure 6.18 gives an example of this for Run 71.

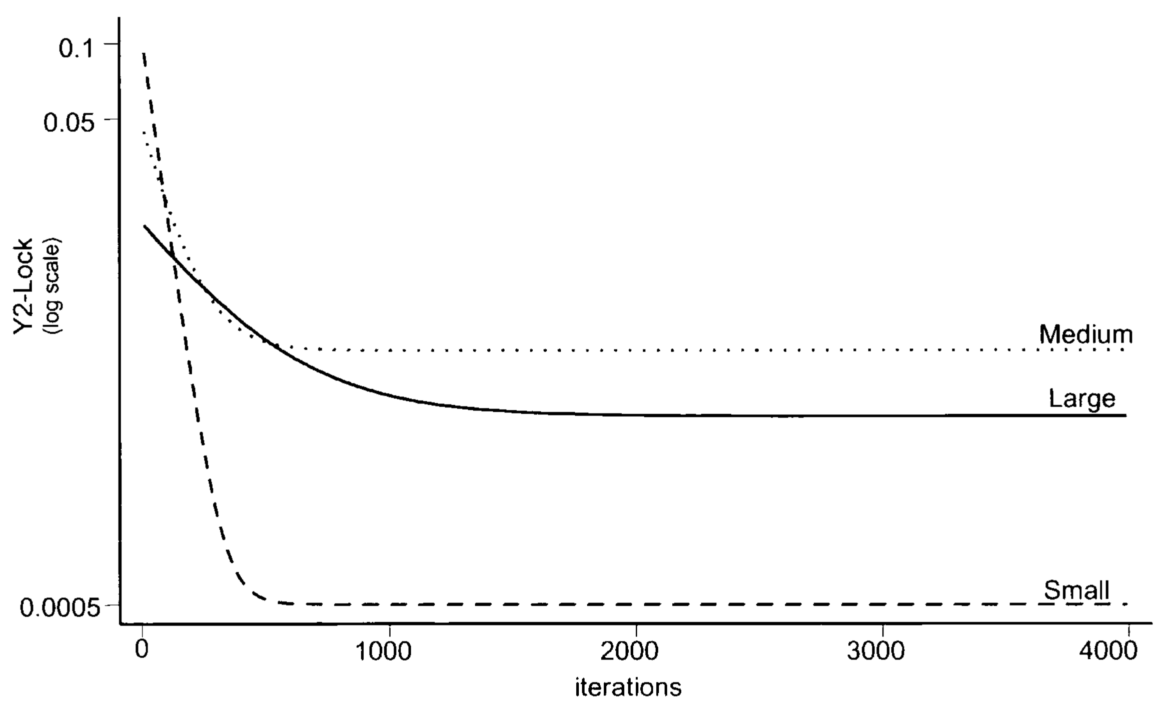


Figure 6.18 Expapp curves fitted to small, medium and large clast behaviour - Run 71

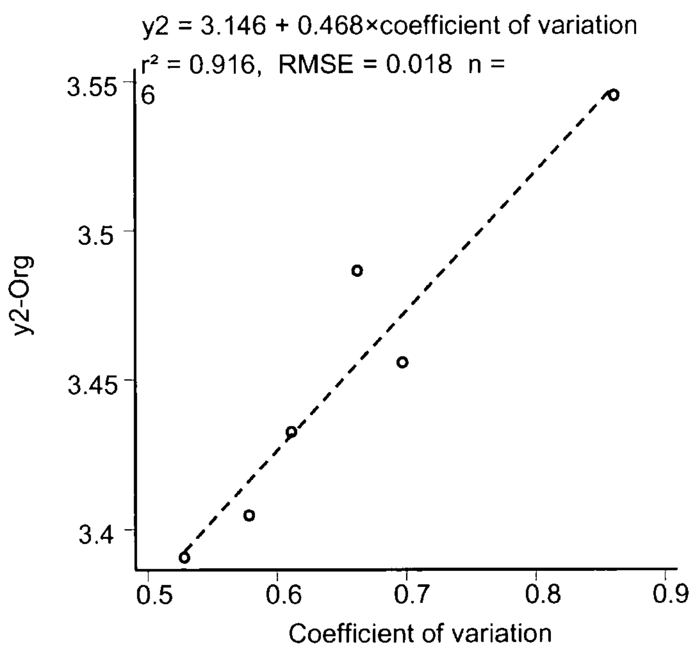
Both a surprising and important control on surface dynamics is apparent (Figure 6.18). The fitted curves indicate the mean probability of each clast size moving through the experiment, as represented by y2-Lock. At the start of the experiment (iterations = 0) the clast Lock directly reflects the probability of Lock determined by clast size, with small moving most freely, then medium and finally large. As the surface modifies under the experimental conditions the behaviour of each fraction rapidly changes. After 333 iterations the small size fraction becomes the most static clast size. For a period of 268 iterations beginning at iteration 250 the largest clast fraction is the most mobile, despite having the lowest probability of Lock. The final equilibrium state of the experiment shows medium clasts being the most dynamic, followed by the large and finally the small clasts. The development of surface patterning may therefore be expected to be more pronounced on larger clast dominated surfaces. The smaller clast sizes may be to responsive to process action to form patterning as they tend not to become tessellated into locking structures. As a size group, small clasts maybe considered to be too stable to form self-organized.

The perhaps surprising nature of behaviour is explained as a result of the complexity of interactions of different clast sizes and has implications that can be extrapolated to the field. At the outset of the experiment clasts are randomly but uniformly dispersed across the matrix. As the experiment commences clasts begin to come to rest against those which are less mobile. In the example above the surface is dominated by large clasts. The small clasts become lodged behind larger clasts which are less mobile. After 125 iterations the majority of small clasts are jammed behind medium and large clasts. Small clasts can only move if the medium or large clast moves. A queuing effect occurs, whereby the movement of the smaller mobile fraction is dominated and controlled by the larger clast sizes. The medium and large clasts in effect act as core stones supporting structures of smaller clasts sizes. This suggestion is supported by observations of the clast structures within polygonal forms (Plate 6.1). The medium fraction remains more mobile than the largest fraction, in this instance as it acts both as a core stone but retains mobility due to its higher probability of clast movement.

Intuitively the most mobile clast should be those which are most probable to move. On surfaces with a variety of clast sizes it is those clasts which dominate and support surface structures that are the most mobile, often those of a larger size. This is of particular importance in the northeastern Badia where hydraulic transport and hence preferential clast size movement is unlikely. Even if the smaller clast fraction is more likely to be mobilized, the dynamics of the whole surface may be dictated by the larger clasts fraction.

ii. Organization

Contrary to measures of stability, measures of surface structure and pattern appear to correlate well with clast sorting variables. Figure 6.19 shows the relationship between Cv_b, box fractal dimension, and Org. The relationship between y2-Org is statistically significant (1% significance level when n = 6, r^2 = 0.917).



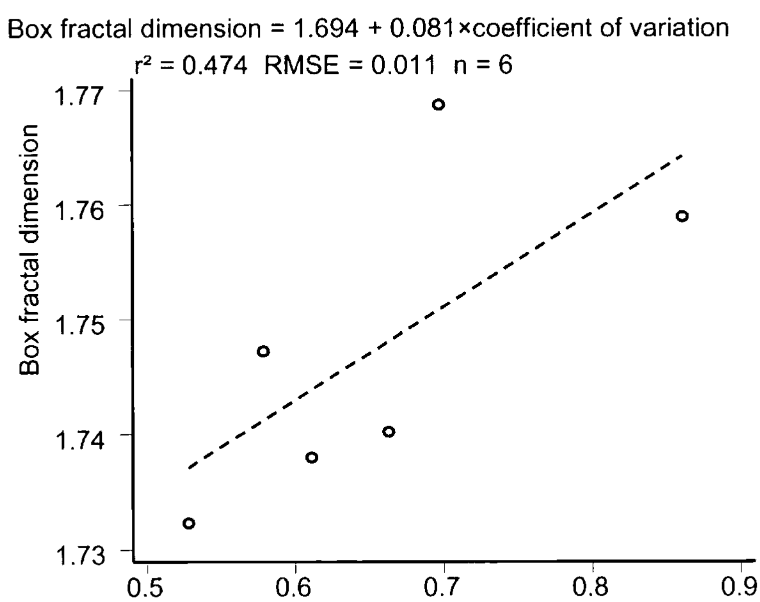
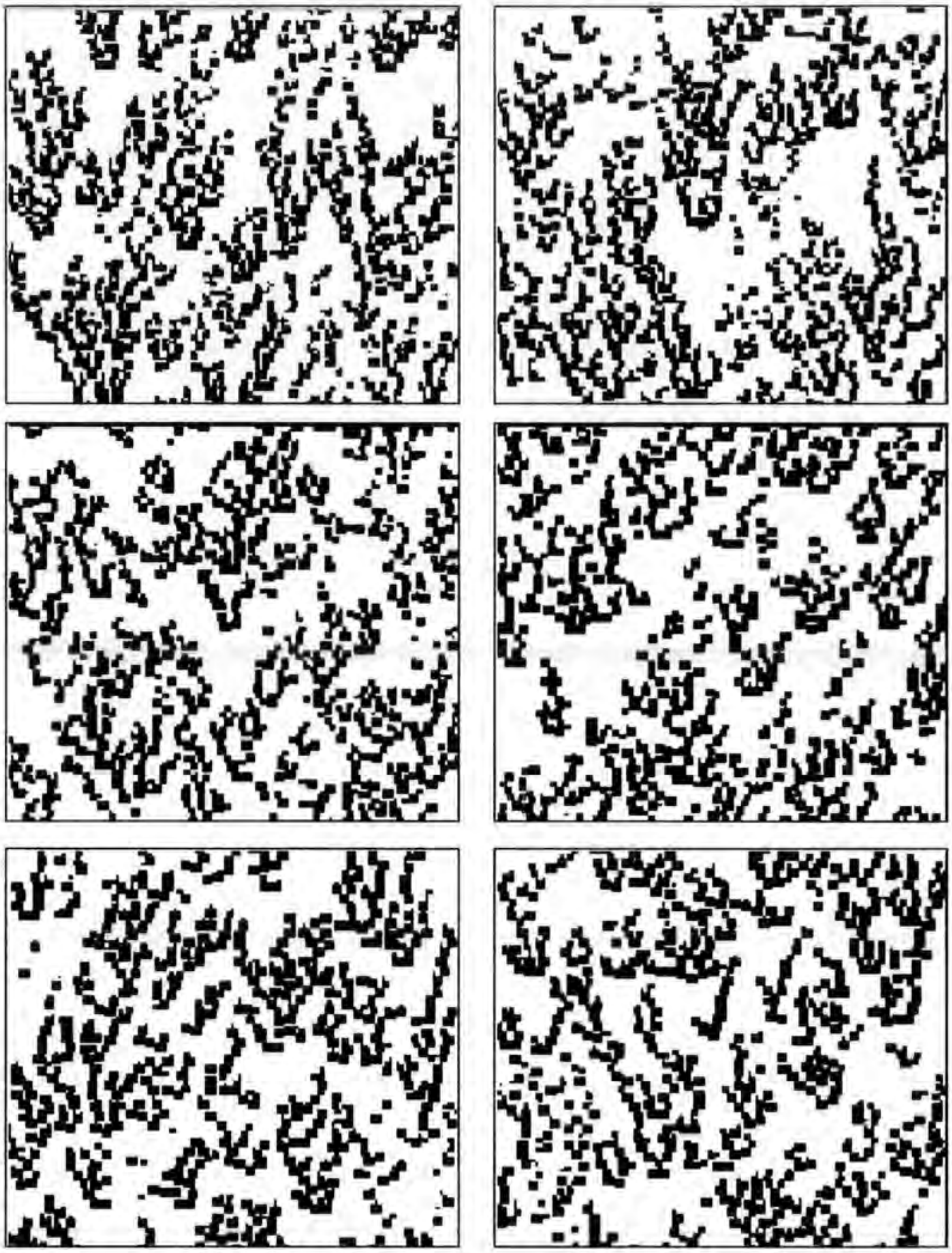


Figure 6.19 The relationship between coefficient of variation and y2-Org, and box fractal dimension

The implication is that the sorting of the clast population influences the nature of resulting surface structure. The strength of the relationship between Org and Cv_b suggests that as sorting increases and a more uniform clast distribution emerges, with the surface tending to form clusters. The corresponding increase in fractal dimension tentatively suggests a tendency towards greater self-similarity and linear order with increased clast size sorting. These suggestions are supported by a visual assessment of model output (Figure 6.20). Evidence of linearity in surface form is apparent where smaller clasts queue behind the larger cores stones. All surfaces show areas that are devoid of clasts, lineations and clusters. Fractal dimensions appear lower than those established earlier for surfaces with variable percentage cover. This implies that under experimental conditions where the surface supports a mixed clast size distribution, clusters rather than regular ordered features tend to form. On a larger matrix the clustering and segregation of clasts into structures may represent a higher order of structure, but this is beyond the scope of this experiment.

Mixed clast size surfaces appear to behave in a complex manner. Interactions vary throughout the course of the experiment and the relative dominance of each clast size in controlling the surface dynamics alters. Order and structure emerges as the sorting of the clast population increases. The implications of this in the northeastern Badia are two fold. Firstly, all of the surfaces surveyed using the image analysis show a dispersed clast size distribution, returning high values of Cv_b. The response of the northeastern Badia surfaces is likely to be equally complex and variable as that in the model. Again, visually similar results when quantified represent a systematic variation in the spatial organization and character of the surfaces which can be linked to minor perturbations in the controls on clast interactions. Secondly, the model suggests a greater tendency to clustering, rather than distinct self-similarity. Under these modelling conditions it is difficult to explore whether clustering at this matrix size is a reflection of pattern of a higher order. In the field examples patterning are linear, forming networks (Figure 6.20). An organized surface can be either clustered or lineated. Structure does not necessarily have to look aesthetically pleasing to be statistically organized.



67	68
69	70
71	72

Figure 6.20 Final model output runs 67 – 72

3.7.4 Run set 4 – The influence of slope angle

Classification of the slopes in the northeastern Badia has shown a range of slope forms and angles. Slope angles, although generally low, vary between locations. The relationship between slope angle and surface character and the relationship between slope angle and surface hydrology has been shown to be by no means straight forward. A model is developed to explore the relationship between the dynamics and organization of the surface as influenced by changing slope angle. A surrogate control on slope angle is used in the model. Slope here is effectively a control on the rate of change, or speed with which the model works. The complexity of clast interactions means that a change in slope in not just a speed regulator on the model, but it is found to dictate the nature of surface form variations and structure. The effect of altering the speed of the model is now investigated. A series of experiments, Runs 73 – 102, is designed to examine the influence of an incremental increase in slope angle on the three clast sizes (Table 6.11).

Run set	Percentage cover = 33% (small clasts only)			Percentage cover = 33% (medium clasts only)			Percentage cover = 33% (large clasts only)		
Run number	73 to 82			83 to 92			93 to 102		
	For intermediate runs			For intermediate runs			For intermediate runs		
Matsize	125	125	125	125	125	125	125	125	125
Totcl	5156	5156	5156	1289	1289	1289	573	573	573
Small rocks	5156	5156	5156	0	0	0	0	0	0
Medium rocks	0	0	0	1289	1289	1289	0	0	0
IT_{max}	4000	4000	4000	4000	4000	4000	4000	4000	4000
Sangle	1	$1-(0.1)^a-0$	0	1	$1-(0.1)^a-0$	0	1	$1-(0.1)^a-0$	0
p(small)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
p(medium)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
p(large)	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
f_{diag}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Dfddiag	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
F_{lat}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Repetitions	10 per rule set			10 per rule set			10 per rule set		

Table 6.11 Run configurations – Runs 73 – 102.

i. Stability

Final levels of surface Lock appear to be dictated by the slope angle of the surface. It has already been demonstrated that surface stability is a function of clast size. Results indicate that in this experiment the three clast sizes respond differently to changes in slope angle. There is a highly significant relationship between stability and slope angle for each clast size fraction; small r^2 = 0.994, medium r^2 = 0.988, large r^2 = 0.987 (1% significance for 8 degrees of freedom = 0.765). In this experiment, slope angle controls the final probability of clast movement. On these surfaces the clasts are still free to move and are not significantly jammed or locked together. Slope angle has been shown to control to final rate of surface activity, but it can also be related to the speed with which the surfaces stabilize, which has implications for the surfaces in the Badia. Figure 6.21 illustrates Expapp curves fitted to the y2-Lock output for Runs 73 – 82. It is clear that as slope angle increases the final stable state of the surface tends to be more mobile.

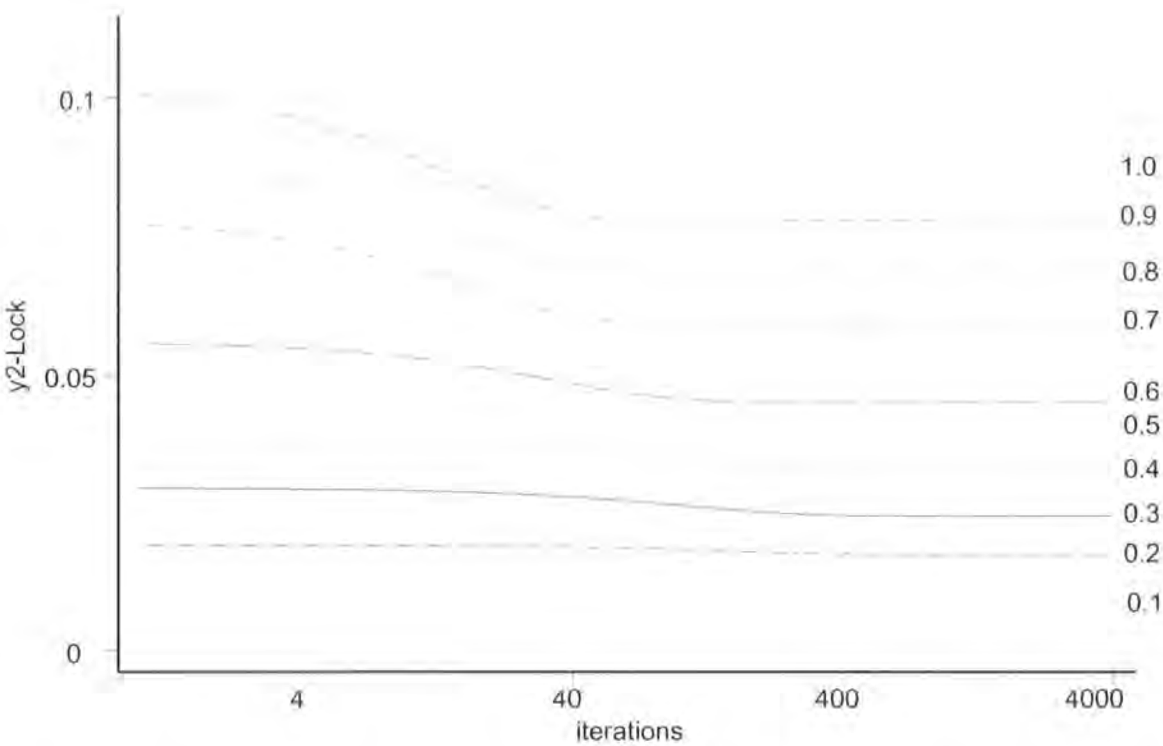


Figure 6.21 Influence of slope angle on Lock – Runs 73 – 82. The value of slope value is labeled on each line

Figure 6.21 also suggests that the rate of change to a stable state is also increased by an increased slope angle. Figure 6.22 reiterates this, showing a strong relationship between k-Lock, the rate of change in the Expapp model and slope angle.

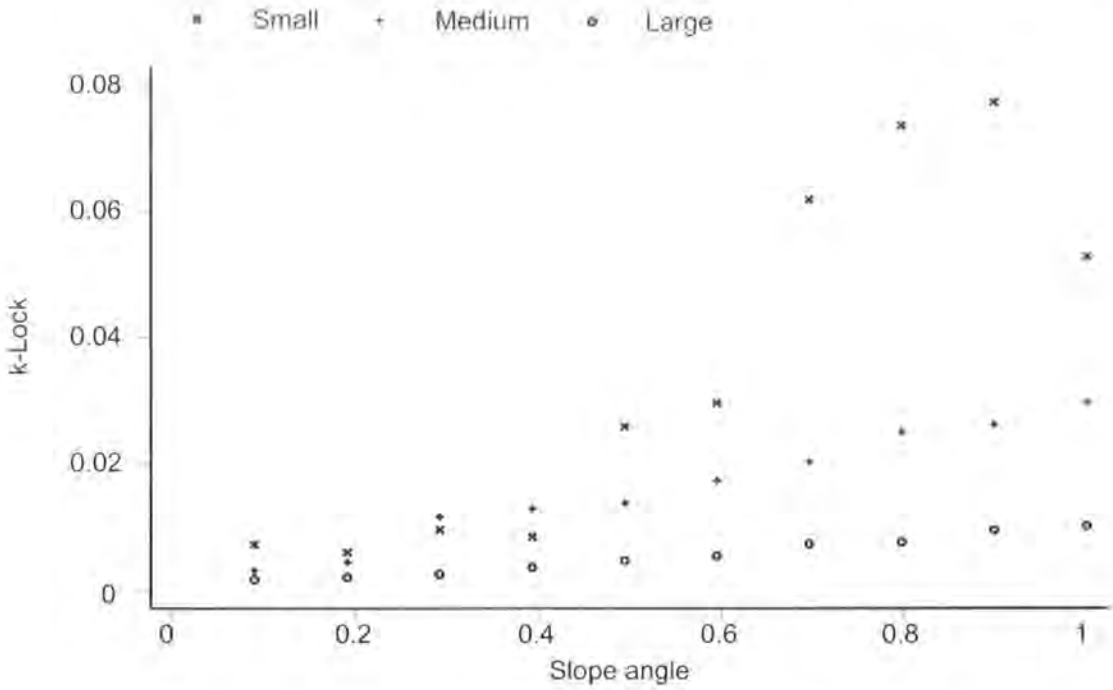


Figure 6.22 Relationship between slope angle and the rate of change to stable state

Rates of change to a stable state increase more consistently with increased clast size. This is a reflection of the increased dampening incurred by the greater complexity of multiple interactions experienced on larger clast dominated surfaces. For all clast sizes the rate of change to a stable state increase with slope angle. The implication of this to the northeastern Badia concerns the condition of various portions of a slope profile. The lower response time for adjustment on higher slope angles means that surface modification could be expected to be greatest at these points. Low angled slopes may represent immature surfaces. The degree to which the surface can be modified maybe limited by the low slope angle and reduced activity of gravity driven processes. The situation is further complicated in the field by up-slope angle, which has previously been shown to be an important control on local slope form and process. A low slope angle at the base of a concavity may be significantly modified not as a result of its local slope angle, but rather as a product of the up-slope conditions. The model is not capable as assessing the influence of whole slope profile form. Figure 6.21 and Figure 6.22 suggest that at lower slope angles the modification of the surface is muted.

ii. Organization

There is a significant relationship between the values of slope angle and y2-Org. The nature of the link between slope and y2-Org varies considerably between clast fractions. For small clasts the relationship is negative, with clustering apparently reducing with increased slope, whereas on medium clast dominated surfaces clustering increases with slope angle. Both relationships are statistically significant (r^2 = 0.632 for 5% confidence limits). Clast size and the resulting variable nature of clast interactions act as a significant control on surface dynamics. The relationship between slope angle and the behaviour of the largest clast fraction is not statistically significant.

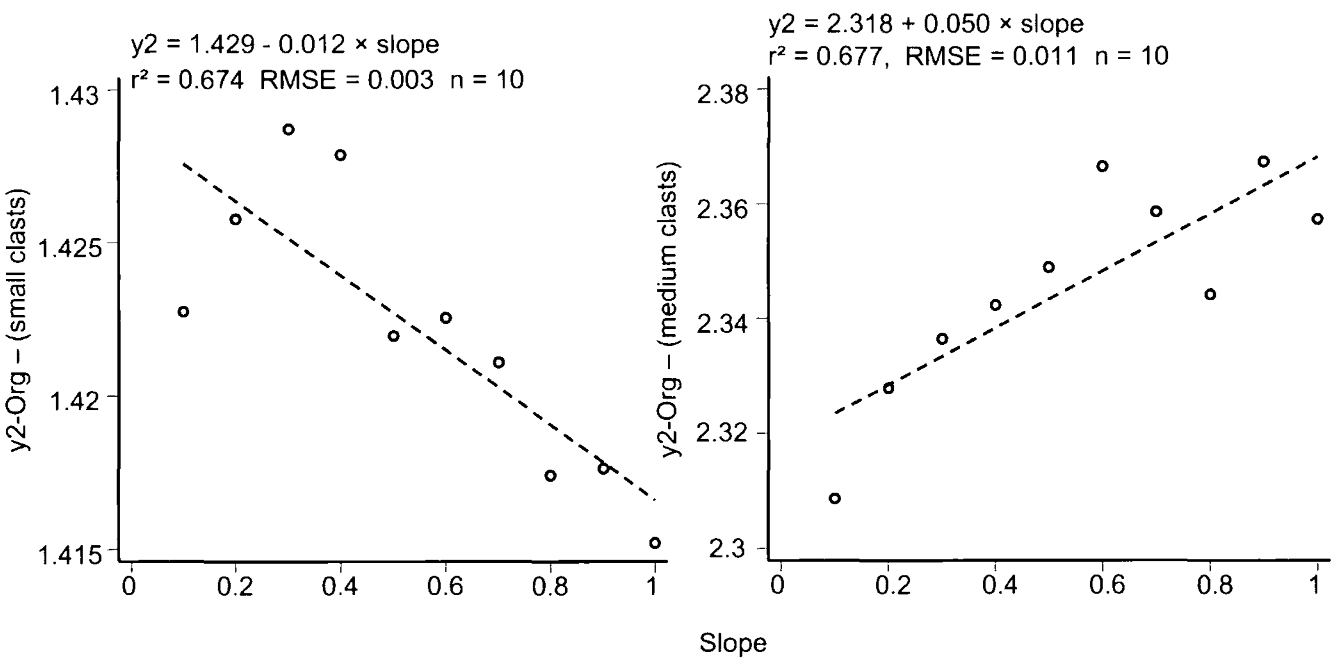
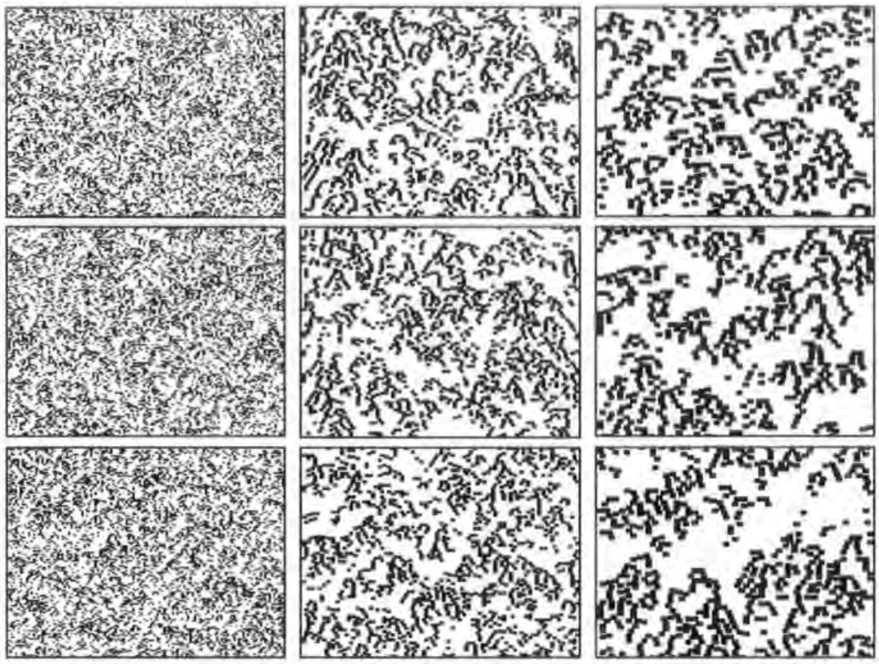


Figure 6.23 Relationship between slope angle and y2-Org, small and medium clast sizes

Visually the differences between clast size behaviour are difficult to discern (Figure 6.24). It is clear that the absolute range in values of y2-Org remains small but nonetheless distinct differences exist in clast size behaviour.



73	83	93
77	87	97
82	93	102

Figure 6.24 Output images Run set 4

Analysis of variations in fractal dimension show an insignificant relationship with in y2-Org with slope angle (small r^2 = 0.024; medium r^2 = 0.035; large r^2 = 0.248, 5 % significance when N = 10, r^2 = 0.632). Slope is therefore a poor predictor of surface fractal dimension. Modification in the surface tends to form clusters, the distinction of which is dependant on clast size. Self similarity and order as described by the box fractal dimension is not influenced by slope angle. This reiterates the distinction between the nature of structure described by y2-Org, namely clustering, and that described by the fractal dimension, namely self-similarity. Using box fractal dimension as a measure of surface pattern and structure suggests that slope is not influential. It is clear however that subtle differences emerge in the degree of surface clustering with variations in slope angle. The rate and nature of change with which the surfaces adopt a final asymptotic condition of stability is linked to slope angle but the final condition itself is not linked to slope form. Applied to the northeastern Badia the model results support the findings which suggest that slope as a sole predictor of surface organization is not reliable.

3.7.5 Run set 5 – The influence of edge weighting

Dunkerley (1995) advocated the use of what he termed appropriate statistics to describe and explain coarse clastic surfaces. He suggested the use of edge, area and volume weighted mean intermediate axes was a more appropriate method of quantifying surfaces as the weighted means represent more closely the controls on surface processes. In the image analysis and within the context of the model, edge and area can be directly measured from which volume can be extrapolated if clasts are assumed to be perfect cubes. Weighting in the model is used as a surrogate for the propensity for a clast to undergo movement. The behaviour of a surface whereby the probability of movement (p(clast)) is proportional to edge-length, area or volume, is be compared. The following series of experiments is designed to examine the influence of weighting the probability of clast movement to edge length, surface area and a surrogate value for clast volume. Results of these experiments help to suggest the relevance of weighted measures as a means of understanding clastic surface dynamics, if an iterative mechanism of surface modification is appropriate.

In the model run-sets previously undertaken thus far the ratio of probabilities for each of the size fractions has been based on clast area. Four subsets of tests were undertaken. The first, Runs 103 – 105, examines surfaces with a mixed clast size distribution. Runs 106 – 108, Runs 109 – 111 and Runs 112 – 114 consider small, medium and large clasts respectively for comparison, each with an area, edge and volume weighting. Again variables not under examination are maintained at a constant level. Run configurations determined using the weighting system described in Table 6.12 are given in Table 6.13 and Table 6.14.

		Area	Edge	Volume
Relative Weightings	Small	1	4	1
	Medium	4	8	8
	Large	9	12	27
	Total	14	24	36
Unit weighting (1/ Total)	Individual	0.0714	0.0417	0.0278
Clast Weightings = Relative weightings x Unit weighting	Small	0.0714	0.1667	0.0278
	Medium	0.2857	0.3333	0.2222
	Large	0.6429	0.5	0.75
		Reciprocals		
Final clast weightings	Small	0.9289	0.8333	0.9722
	Medium	0.7142	0.6667	0.7778
	large	0.3571	0.5	0.25

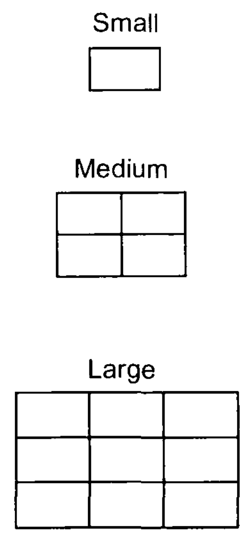


Table 6.12 Calculation of edge, area and volume weighting

Run set	Percentage cover = 33 %, clasts in ratio 3 (small) : 2 (medium) : 1 (large), weighted by area			Small clasts only (cover = 33 %)		
Run number	103	104	105	106	107	108
Matsize	125	125	125	125	125	125
Totcl	1547	1547	1547	5156	5156	5156
Small rocks	773	773	773	5156	5156	5156
Medium rocks	516	516	516	0	0	0
IT_{max}	4000	4000	4000	4000	4000	4000
Sangle	0.5	0.5	0.5	0.5	0.5	0.5
p(small)	0.929	0.833	0.972	0.929	0.833	0.972
p(medium)	0.714	0.667	0.778	0.714	0.667	0.778
p(large)	0.357	0.5	0.25	0.357	0.5	0.25
f_{diag}	0.25	0.25	0.25	0.25	0.25	0.25
Dfddiag	0.125	0.125	0.125	0.125	0.125	0.125
F_{lat}	0.25	0.25	0.25	0.25	0.25	0.25
Repetitions	10 per rule set					

Table 6.13 Run configurations – Runs 103 – 108

Run set	Medium clasts only (cover = 33 %)			Large clasts only (cover = 33 %)		
Run nreiumber	109	110	111	112	113	114
Matsize	125	125	125	125	125	125
Totcl	1289	1289	1289	573	573	573
Small rocks	0	0	0	0	0	0
Medium rocks	1289	1289	1289	0	0	0
IT_{max}	4000	4000	4000	4000	4000	4000
Sangle	0.5	0.5	0.5	0.5	0.5	0.5
p(small)	0.929	0.833	0.972	0.929	0.833	0.972
p(medium)	0.714	0.667	0.778	0.714	0.667	0.778
p(large)	0.357	0.5	0.25	0.25	0.25	0.25
f_{diag}	0.25	0.25	0.25	0.25	0.25	0.25
Dfddiag	0.125	0.125	0.125	0.125	0.125	0.125
F_{lat}	0.25	0.25	0.25	0.25	0.25	0.25
Repetitions	10 per rule set					

Table 6.14 Run configurations – Runs 109 - 114

i. Stability

The image analysis in the northeastern Badia suggests that the consideration of the edge lengths, areas and volume of clasts through process appropriate weighting provided a valuable link between surface form, slope and hydrology. The change in relationship between the type of edge weighting and the stability of the surfaces appears systematic. Table 6.15 shows the final mean value of stability for each of the weighting regimes for surfaces with a mixed clast size distribution.

Weighting	y2-Lock	k-Lock
Edge	0.0229	0.0199
Area	0.0195	0.0202
Volume	0.0161	0.0226

Table 6.15 Influence of weighted means on surface Lock

Weighting the probability of clast movement by a measure of a higher dimension, for example area and volume, reduces the final stability of the surfaces. Three-dimensional volumetric weighting leads to a lower value of y2-Lock than the one dimensional edge length weighting. The surfaces under volumetric weighting are more stable. The difference in results is explained as a function of the shift in ratio of the relative influence of the large to small clasts controlling the surface dynamics. In volumetric weighting, the ratio of small to medium to large clasts is 1 : 8 : 27, whereas under the edge weighting condition this ratio is 1 : 2 : 3. As the dimension of the weighting factor increases, the proportional influence of the largest clast fraction in the distribution is amplified geometrically. Under volume weighting the probability of movement for a large clast is, in relative terms, low. As these clasts tend to dominate the behaviour of mixed populations, as shown previously, the rate of change in surface modification is low.

An assessment of which of the weighting strategies is more appropriate to the conditions of the northeastern Badia is difficult to undertake in the absence of direct measurement of clast movements in the field. The diversity of results generated by the different methods of weighting in the model has some interesting implications. In the field it has been noted that the dominant process in action may alternate between locations. In parallel is the systematic variation of ground surface form, which as demonstrated has a profound influence on surface behaviour. It is plausible that the importance of different facets of the surface character have a variable influence on surface form between different locations. Take for example a storm on a slope profile. At the top of the slope clast area may play a critical role in intercepting raindrop impact or concentrating overland flow. At the mid-point of the slope, where flow depths and ponding are such that the impact of raindrops is negligible, edge length may be of greater importance in partitioning infiltration from overland flow. At the base of the slope, where wetting depths are greatest and hence shrink - swell processes may be at their greatest, the volume of the clast may play an important role as its mass, which is directly proportional to volume, may determine the tendency of the clast to topple or settle on the sediment surface. The model has shown that variable weighting can alter surface movement. If behaviour is relative to different aspects of the clast surface in the northeastern Badia, then it would not be unreasonable to expect that surface dynamics vary accordingly, as suggested by the model.

ii. Organization

Surface structure is dictated by the shifting ratio of importance of small to large clasts as the dimension of the weighting employed increases. Table 6.16 shows the relationship between y2-Org and the weighting type and also shows the variation in box fractal dimension.

Weighting	y2-Org	Box fractal dimension
Edge	3.5418	1.7603
Area	3.5778	1.7629
Volume	3.6090	1.7688

Table 6.16 Org and fractal dimension relative to weighting type

Variation in Org appears systematic, but is not pronounced. Increases in clustering, suggested by an increased level of y2-Org corresponds well with increasing values of the box fractal dimension. The surfaces do not show a preferential tendency to either clustering or self-similarity, but rather both appear to increase as the dimension of the weighting increases. Variable levels of surface organization previously identified as a result of the influence of weighting are to an extent reflected in the field. Only very subtle variations in surface organization and structure are apparent from the spatial analysis of the model output. Natural variability of the surfaces in the field may act to mask such a subtle variation incurred by the effect of the changing importance of different attributes of the clasts in controlling surface processes and form. The tendency the slopes of the northeastern Badia to exhibit systematic variations in surface organization is commonly shrouded in naturally occurring noise. Visually it is difficult to explicitly say which surfaces are the most ordered (Figure 6.25). Without an entirely robust method of comparison between two dimensional patterns or levels of organization, the distinction of this type of phenomena in the field is virtually impossible. Examining various weighting parameters has shown another potential control on surface form which can directly be extrapolated to the geomorphology of the northeastern Badia surfaces. Specifically the variable role and dominance of process action down the slope profile may well be influenced and represented most appropriately by clast measures with variable weightings.

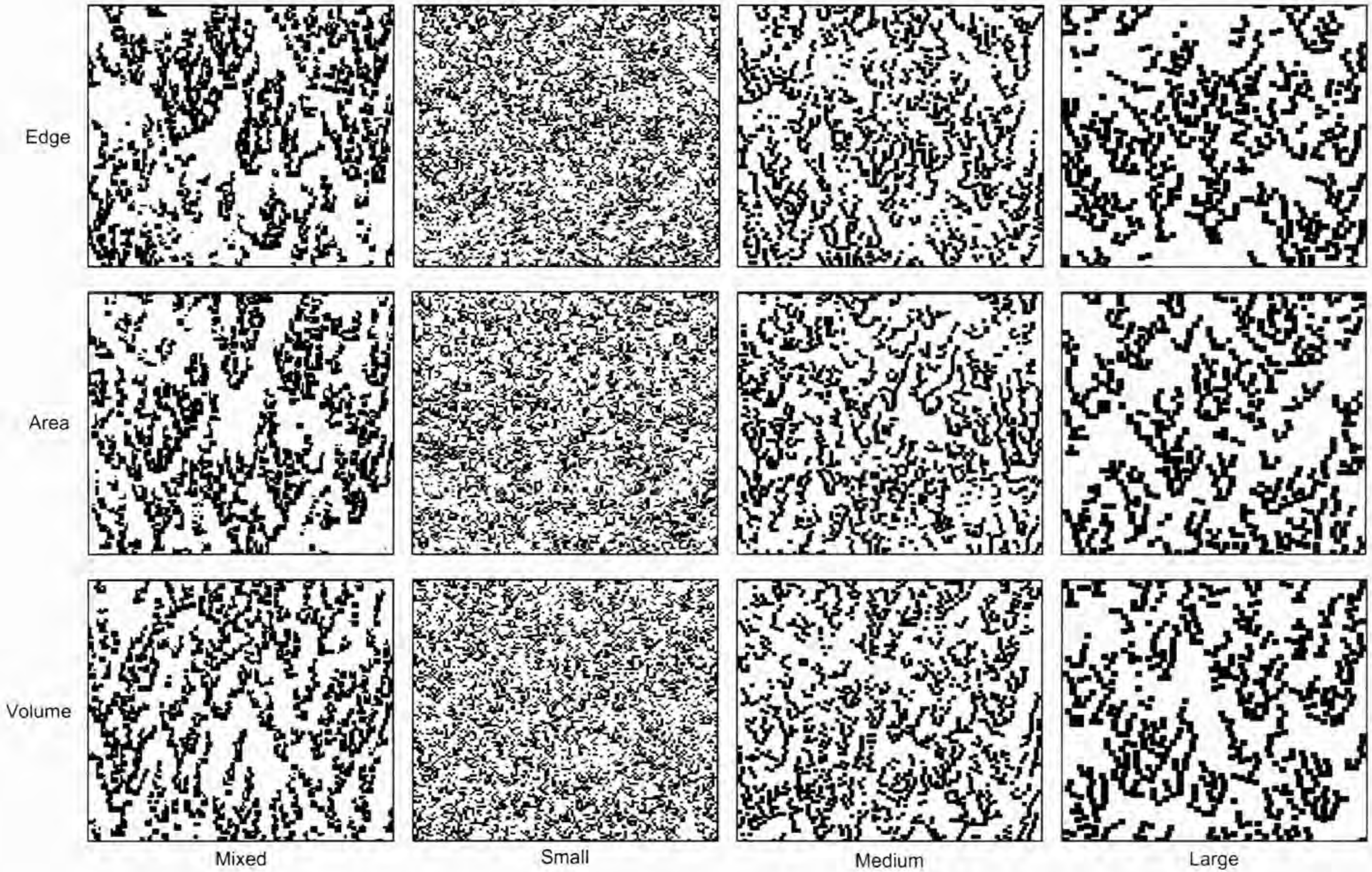


Figure 6.25 The influence of edge weighting and clast size on surface form. Final model output – Run set 5

3.7.6 Run set 6 – The influence of randomly generated model conditions

A final set of run configurations was undertaken to examine the response of the surface to randomly generated conditions. The results so far have been based on systematically chosen model conditions, with linear iterative incremental changes in model parameters, which mirror variations noted in the field. Model output and behaviour can be related both qualitatively and quantitatively to observations from the field, both in terms of form and process.

This series of experiments aims to examine whether the behaviour previously seen also occurs under random conditions. If so, then it could be suggested that the variations in model response and potentially in the field, may be entirely due to the action of random processes and hence be due to chance. Conversely, if random conditions fail to replicate the behaviour observed then tentative suggestions can be made that the surfaces do not behave under random conditions and that a certain degree organization and feedback between surface form and process is responsible for contemporary form and process on the northeastern Badia slopes. A series of experiments is developed within which the probabilities of clast movement, slope and the interclastic frictions are determined by random number generation between 0 and 1. Dfddiag is maintained at half the value of f_{diag} to sustain logical totalistic behaviour of multiple clasts (Table 6.17). The five experiments undertaken comprise a mixed clast size distribution with small to medium to large clasts in the ratio 3 : 2 : 1, at a fixed ground cover percentage of 33 %.

Run set	Cover percentage (33 %), 3 : 2 : 1 ratio of small, medium and large				
Run number	115	116	117	118	119
Matsize	125	125	125	125	125
Totcl	1547	1547	1547	1547	1547
Small rocks	773	773	773	773	773
Medium rocks	516	516	516	516	516
IT_{max}	4000	4000	4000	4000	4000
Sangle	0.7044	0.3769	0.4374	0.4275	0.0015
p(small)	0.7336	0.4192	0.2825	0.4451	0.0752
p(medium)	0.0763	0.1794	0.1281	0.1089	0.0484
p(large)	0.5091	0.1306	0.6128	0.2780	0.9861
f_{diag}	0.7560	0.4930	0.7345	0.8401	0.5767
Dfddiag	0.3780	0.2465	0.3673	0.4200	0.2883
F_{lat}	0.7362	0.0753	0.9597	0.9671	0.7995
Repetitions	10 per rule set				

Table 6.17 Run set configurations – Run set 6

i. Stability

The random generation of run conditions produced a variety of surface behaviours. Where unusual surface behaviour occurs, it appears that it can be directly related to a single low probability of clast movement. The results of the experiments are show in Table 6.18.

Run	Mean f(move)	Mean p(move)	Y2-Lock	Rate of change (k-Lock)	RMSE (Expapp)
115	0.623	0.506	0.273	0.073	0.002
116	0.272	0.277	0.010	0.054	0.000
117	0.687	0.365	0.067	0.001	0.002
118	0.742	0.315	0.112	0.046	0.002
119	0.555	0.278	1.267	0.000	0.001

Table 6.18 Influence of randomly generated run configurations on surface Lock

Differences in the behaviour of the surfaces can be explained by examining the minimum probabilities of movement and friction. In run 115, p(medium) = 0.076, in run 116 f_{lat} = 0.075 and in run 119 Sangle = 0.0015, p(small) = 0.075 and p(medium) = 0.048. The combined effect of low values of Sangle, p(small) and p(medium) in run 119 result in an effectively static surface, with virtually no clast movement expect at the very start of the experiment, as indicated by a very low value of k-Lock. Run 118, for example, has no significantly low movement or friction values. The surface in Run 118 takes a longer period of iterations to stabilize, and when it does so, it stabilizes with more freedom of movement than the other run set-ups.

Surface movement is sensitive to individual variables. A single low value of either friction or movement can cause a surface to jam very rapidly, even before a structured or ordered state is reached. Under random conditions surfaces are not always able to modify themselves spatially, and so organization is often limited. Surfaces appear to stabilize at levels influenced by purely one contact rule or interaction. The combined influence of multiple interactions appears to be of less importance when one interaction rule has a magnitude which is significantly different to the rest. The implication for the northeastern Badia is that if for some reason, be that external or internal to the slope system, one type of interaction limits clast movement substantially more than other interactions, then the surface may behave in a static manner, showing limited dynamics and modification.

i. Organization

Org statistics and the box fractal dimension show a variety of surface structure and levels of organization emerging from this series of experiments (Table 6.19).

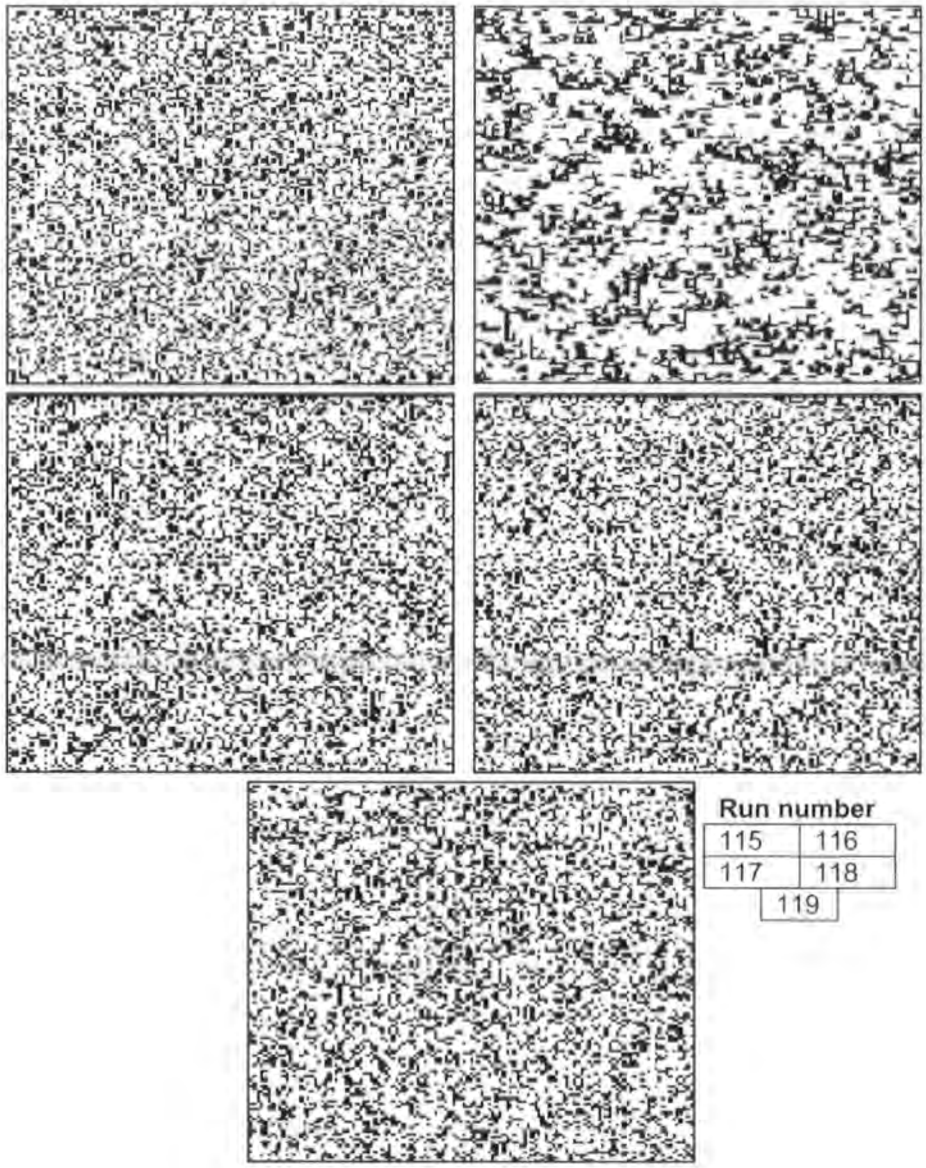
Run	y2-Org	k-Org	Box fractal dimension
115	1.2002	0.0947	1.9056
116	2.0627	0.0021	1.8537
117	1.2120	0.0739	1.8962
118	1.2202	0.1452	1.9007
119	1.2674	0.0003	1.8973

Table 6.19 y2-Org and box fractal dimension – Run sets 115 – 119

y2-Org varies between Runs 115 to 119. The most noticeable departure to clustering is seen in Run 116. Run 119 experienced relative little modification shows no significant departure away from a completely random spatial distribution. The rate of change to Org, represented by k-Org reflects to role of single low probabilities of movement or high levels of friction in the dictating the outcome of the model. Under a randomly generated distribution the mean number of contacts for all clasts on the surface is 1.279. Departure from this value indicates the degree of modification. Runs 115, 117 and 118 all show values less than 1.279, whereas the static surface in Run 119 is closer to this figure. The box fractal dimension again reiterates this suggestion. The most highly modified surface seen in Run 116 demonstrates a higher degree of linearity returning a lower fractal dimension. The remaining four runs show no discernable differences or departures from the initial random condition, as is reflected in the model output images in Figure 6.26.

Under random conditions that model generates a variety of outputs which appear to be commonly related to extraordinary values of either frictions and or probabilities of clast movement. The model has demonstrated that under randomly generated conditions, order and structure and a stable surface form can emerge. In the northeastern Badia it is unlikely that random conditions exist. Feedbacks between clast size and shape should logically effect the nature of interactions between clasts. Systematic variations in surface character have been noted and related to slope and process action. It would seem logical and plausible to assume that the nature of interactions and feedbacks on the surface is equally non-random.

Figure 6.26 Model output images – Run set 6



6.8 Discussion

The model developed as part of this study generates a valuable series of results. The model structure behaves in a manner which can be conceptually linked to the behaviour of the surfaces of the northeastern Badia. Rather than a direct visual comparison between the model output and the real world environment, the quantitative assessment of the dynamics and behaviour of the model appear to closely mirror features observed in the field. Temporal variations in the model output match spatial variations observed at various positions down-slope in the field. The model succeeds in explaining links between clast form and surface spatial configuration where the previous regression analysis, using a linear model, only returns insignificant relationships. As such, the model is a good predictor of where pattern or structure does and does not occur. In many instances an incremental, or linear, variation in model parameters results in a distinctly non-linear or chaotic response in surface behaviour and form.

The Expapp model, which suggests an exponential approach to an asymptotic stable state, appears to be an appropriate method of describing the stabilization of the modelled surfaces. The model suggests that even though the surfaces on the whole do not obtain a static condition, they do maintain their form at a consistent level. The value of the stable state is intimately linked with both the character of the whole surface and the character of the individual surface clasts. Additionally, the rate at which the surface reaches a stable state is controlled by the specific characteristics of the surface clasts.

The parametric analysis of the influence of clast variables has demonstrated that subtle variations in clast interactions have a significant influence on the behaviour and final state of the surface. The model is sensitive to minor perturbations in clast interaction parameters. In several instances surprising results are generated. For example, on a surface with a mixed clast size distribution, it is not the most mobile clasts which are the most free to move but rather the larger clasts which act as core stones to lock together and inhibit the movement of the other clasts on the surface.

Clast size, as a commonly quoted measure of surface form, is a vital control on the model behaviour. It is apparent that as the size of the clasts increases the complexity of the interactions between clasts increases. In the model small, medium and large clasts often all behave in a very different manner. The various clast sizes appear to behave and respond to the initially random conditions in a variety of ways. An example of an implication of the model results is the difference in dynamics of surfaces on different basalt types, due to the control of clast form and size distribution. If the initial starting condition of clast form is dictated by the jointing structures or mineralogy of the underlying basalt, but the subsequent modification of the surfaces is as a result of similar processes regimes, then all surfaces will tend not to evolve to a single characteristic form. The final surface condition is linked directly to the initial conditions and the nature of clast interactions which this dictates. The diversity of surface form and variations in surface form observed may therefore be a function of different surface responses to a similar pattern of climatic forcing, rather than a series of snapshots at various stages of a linear path of surface evolution.

It is difficult to relate the influence of local slope to surface form variations in the field. The logical assumption would be to assume that an increased slope angle acts purely as an accelerator to the surface processes but slope has been found to influence the various clast sizes in a different manner in the model. Given the non-linear response of many of the other parameters studied, the influence of slope has been found to be equally complex. The distinction in surface behaviour with slope has several implications for a whole slope understanding of surface behaviour. Slope may influence the rates and the magnitude of various fractions of the clast size distribution in different ways. Changes down-slope cannot therefore be directly related to slope angle alone.

The examination of edge weighting raises the suggestion that the role of dominant processes may change with position down-slope or across the landscape. At the top of a slope profile, where raindrop impact in the dominant control on sediment mobilization and surface modification, it is the planimetric projection of the surface or clast area that is a vital control on surface process and modification. At the slope mid-point where runoff depths are increased, the transmission of water into and across the surface is more closely dictated by clast edge lengths. At the slope bottom, where sediments are saturated, it maybe clast volumes which hold a more significant control as they are effectively suspended in the sediments and their position directly dictated by clast size.

Given the ages of the surfaces, it may be expected that they should be considered to be tending towards mature landforms. The image analysis and the experiments on surface hydrology have demonstrated that there is a close symbiosis between contemporary form and process, suggesting that the surfaces are dynamic and responsive to contemporary conditions. The model demonstrates a similar manner of behaviour. The surfaces obtain a stable state under which they are directly controlled by the state of the interactions between the surface clasts. An interesting line of enquiry would be to explore the response and relaxation of a system to a disturbance or alternation in the base conditions of the model. The modelled surfaces, given their close link to the model parameters, are dynamic. The surface also appears mature in that all have obtained a steady state of behaviour after the completion of the model experiment. Relating this to the northeastern Badia opens some interesting suggestions. Many of surfaces show a departure away from complete spatial randomness in clast arrangement. The model has shown that pattern is not necessarily indicative of a stable or mature surface but is more closely linked to the specific conditions on that surface.

The model has been successful in creating a range of levels of surface organization. As with the image analysis in the northeastern Badia, the model produces a gradual transition in surface organization. Both contradict observation in the field that pattern is a discrete entity which is either present or absent. Systematic variations in the severity of surface organization are apparent with variable in model parameters. All of the surfaces generated show some form of departure from complete spatial randomness. In the field, an observed regularity in the distribution of surface clasts was associated with a spacing dictated by the size of the clasts, relative to the centroid position, and was not therefore considered an artifact of surface dynamics. The model suggests that even slight variations in the levels of surface form variation may be directly to the dynamics of the surface.

The modelling procedure attempted to examine ideas of self-organization and assess how relevant these considerations are to understanding the dynamics of the slopes of the northeastern Badia. There are many apparent similarities between the behaviour and output of the model developed and those of other self-organizing systems (Shultz, 1998). Direct comparisons of model results between this study and others are of little value given the diversity in modelling approaches and interpretations of the concepts of self-organization. Several key features are however apparent. First, the model generates emergent structures (Harrison, 2001) such as dendritic networks, regular lineations and clustering. The model is therefore reliable, as the results generated from different randomly generated starting conditions are very similar, under similar modelled parameters. The nature of the emergent properties cannot easily be discerned from the individual character of the systems components. Second, the model displays homeostasis between the action of process and the resulting form, and vice-versa. The modified surface form alters the way in which the process acts to further modify the surface.

Finally, the model, based on an iterative mechanism of surface modification, appears to be a sensible and successful method of described the development or the land surface forms in the Badia. The interaction between multiple clasts generates complex behaviour from a few simple rules, all of which can be linked to geomorphological variations in the northeastern Badia. The nature of change, the rate of change and the final resultant forms generated by the model appears consistent with the geomorphological variations in the northeastern Badia. What remains an unknown is the actual rates of change and modification of the surfaces. As suggested, what is today considered a high magnitude event may only be considered to be one of many iterative events in the evolution of the northeast Badia surfaces. Conversely, the influence of contemporary small scale events is not known. Only by monitoring the processes directly in the field over a long period can an understanding of the rates of change in this landscape be understood. What is clear from the model and from the field investigation is that the contemporary surfaces are dynamic and reflect the current nature of surface processes.

6.9 Conclusions

Many characteristics of the forms and the nature of changes developed by the clast lock model have close analogies to observations from the Badia. The modelling approach appears to perform well and generates results with direct and logical parallels with the natural surfaces of the northeastern Badia. Clear non-linear effects of linear changes in modelled parameters occur. Consistent changes in measures of surface stability and structure are apparent. The hypothesis of iterative surface modification as the main mechanism of surface organization appears to be true, both in terms of the model output and in terms of the potential nature of process action in the northeastern Badia. Despite the rather crude spatial resolution of the model it provides an alternative method of exploring the linkages between various surface slope and hydrology parameters. If nothing else, it provides food for thought on mechanisms and dynamics of surface modification processes.

Several key points have been raised from this modelling exercise. What often appears on a visual basis to be distinctly organized may only be, on a quantitative basis, only slightly different from a resulting image with little qualitative impression of order. Each of the run setups has raised suggestions with regards the nature of dynamics on the surfaces and identified critical controls on surface form variation. Of equal importance is the consistency of the model in demonstrating where organization does not occur. Finally, levels of structure and the rates with which the surface adjusts can all be linked to the nature of the interactions between the surface clasts.

Chapter 7: Conclusion

Chapter 7: Conclusion

7.1 Summary of thesis

The principal aim of this thesis has been to provide a geomorphological assessment of coarse clastic slopes in arid environments, based on the characterization of form explaining contemporary hydrological processes and modelling ground surface modification.

The main objectives were to:

i. examine the variations in ground surface character on arid coarse clastic surfaces;

ii. examine the variation in slope hydrology and process action on arid coarse clastic surfaces;

iii. explore linkages between ground surface character, slope profile form and surface process action;

iv. use a detailed study of slope form and process as a basis for understanding the temporal development of clast surface organization;

v. apply the results of a model of clast dynamics, to aid the understanding of surface and landscape development.

7.2 Original contribution to knowledge

This study uses a scaled approach which enables links between surface form and processes at the plot scale to be considered in the wider landscape (Chapter 3). Plots are positioned using a systematic technique based on a semi-quantitative nested sampling strategy. Results generated from the plots selected using this method show a consistent, logical and systematic variation in surface character and process action.

Ground surface characterization using the newly developed image analysis technique shows a much greater level of detail and variety in surface measures than previous studies (Chapter 4). The aerial image analysis provides a flexible technique from which a large spatial and statistically significant sample can be collected. Many of the new measures of the in situ nature of the surface form commonly exhibit a more logical nature of change than conventional measures of clastic surface form. The nature of variation within and between basalt types has been shown to be complex and the character of the ground surface varies downslope. In general clast texture becomes smoother, more rounded and the size distribution more constricted towards the base of slope profiles. The nature of downslope change is complex and is linked to slope form, location and underlying geology. Individual basalt flows can be clearly delimited by their surface character, each showing a distinct ground surface character.

Individual measures of surface form commonly show a different nature and magnitude of change down slope profiles. The complexity of the change in surface character is a reflection of relative intensity and dominance of one or more formative processes acting on the surface. The processes include: those which modify individual clasts, for example weathering; those which modify the spatial condition of the surface, or example iterative clast movements; and processes which influence the whole profile surface form, for example the influence of aeolian processes relative to slope hydrology. Many of the variations in surface form can be directly linked to the logical variations in slope process action, described in this study through an examination of slope hydrology (Chapter 5).

The concept of adequacy of surface characterization, suggested by Dunkerley (1995), is validated by the results presented in this thesis. Both weighted intermediate axis means and the actual characteristics of the surface to which these approximate, measured directly by the image analysis, return more significant results than conventional measures of clastic surface form (Chapter 4). The consideration of adequacy and appropriate measures is of paramount importance where variations in surface form are as subtle as those observed in this research.

A series of feedbacks exist between surface form and process (Chapter 5). Surface character has been shown, in some cases, to exhibit convergence downslope to a more constricted style of surface form, the clast size distribution becomes more constricted about a mean down-slope. In other instances, surface form has been shown to be divergent, for example, the degree and character of surface organization increasing down-slope. This highlights the variable nature of processes acting to modify the surface form. A potential feedback mechanism is the presence of clast structures, which may have a significant influence on slope behaviour.

Surface organization of clasts has been quantified using three methods of spatial analysis (Chapter 4). The degree of surface organization can be linked directly to slope and surface cover variables, and in many instances performs better as an indicator of down-slope change in surface form than other variables. No previous attempt to quantify the spatial distribution of clasts on similar surfaces has been made. Marked systematic variations in surface form will hold an equally significant control over slope process and should be considered in any model of slope or catchment hydrology. Mean values of average slope hydrology may hide a significant degree of variation in surface form and process, as seen in the result of this research. The subtle, yet consistent, variation in slope surface character across the landscape, suggests a mechanism of small-scale but spatially extensive iterative surface modification. Additionally, systematic downslope variations in surface character suggest a slope process control on surface form, yet previous work has demonstrated that the mobilization of such massive clasts by overland flow is not a feasible mechanism of clast movement.

The surface characterization has demonstrated that a direct link between surface form and basalt age is not clear. Variation in the surface character on the slopes of a single basalt is complex and appears to be intimately linked with slope form. Variation in ground surface character appears consistent between basalt types. Given the diversity in slope profile form identified within just one basalt type, it is tenuous to suggest an evolutionary link between ground surface character, slope profile form and basalt age from the results presented in this thesis.

The examination of the surface hydrology in the northeastern Badia describes the nature of contemporary slope process activity (Chapter 5). The simulation of high-magnitude rain storm events has been successful in elucidating variations in surface hydrology. A distinct variation in surface hydrology has been noted and is convincingly explained by links with slope, surface profile form and process. The hydrological characteristics examined appear to adhere to the characteristics of surfaces in similar environments (Abrahams and Parsons, 1992). Sediment mobilization, although limited in the experiments, is strongly dictated by splash detachment. Evidence has been presented which suggests that the clastic surface acts to mute the hydrological response of the slope. The muting of the surface response is increasingly apparent towards the base of the slope profile. The top of the slope profile commonly exhibits a flashier and responsive surface hydrology relative to the increasingly muted response further down-slope. The variation in surface hydrology is noted both in terms of response times and volumes of runoff generated.

The role of surface clasts in dictating surface hydrology and rainfall partitioning has been demonstrated through the use of both ring infiltration experiments and plot-based rainfall simulation (Chapter 5). The presence of fine loose sediments is incongruous with a surface which experiences high volumes of high-velocity overland flow. Only limited evidence of gully or rill development is apparent, again supporting the suggestion that the surface clast cover strongly dictates and mutes the action of slope hydrology and overland flow.

An examination of whole slope profiles has demonstrated the complexity of surface hydrology (Chapter 5). The influence of the upslope area, slope angle and the specific ground cover characteristics all control the form of the surface and the efficiency of surface processes. Any attempt to understand catchment scale hydrology must take into account this diversity in surface response. These findings have implications for other studies of catchment scale slope hydrology on clastic surfaces beyond the northeastern Badia. One such method of accounting for the variation in average slope hydrology has been the detailed surface characterization. The characteristics of the in situ nature of the surface derived by the image analysis are highly successful in predicting slope hydrology. The success of the planimetric assessment of surface character as an indicator of surface hydrology shows both the appropriate nature of the characterisation method developed.

A cellular automata model was developed to simulate the spatial modification of the surface clast distribution, as influenced by a range of physically constrained modelled parameters. Many of the features and the responses to variations in model parameters closely mirror variations observed in the field. The model demonstrates complex behaviour in response to linear variations in controlling parameters which are synonymous with naturally occurring variations in surface character. Although spatially crude and simplistic, the behaviour of the model is also logical, showing variations and behaviours which can conceptually be linked to geomorphological processes in the field.

A main benefit of the model is instilling alternative ways of considering the interactions of form and processes on clastic arid surfaces. Non-linearity in the field is also apparent in the behaviour of the model. Subtle variations in individual model parameters appear to hold a significant influence over the outcome of the model. Surfaces are sensitive and responsive to slight variations in surface or clast form. The initial starting conditions of the model are influential on the model behaviour and outcome. The surface cover percentage returns a wide diversity of behaviours and generates a range of organizational and structural characteristics (Chapter 6). In addition the clast size sorting, the angle of slope and the nature of friction between clasts influenced the behaviour and outcome of the model. The surfaces in the model show a quasi-stable state under which an asymptotic level of clast movement and surface organization is apparent. Once they have reached this state surface exhibit only a limited departure similar characteristic to the local scale heterogeneity observed in the field.

The final stable state of the surface, the speed with which the surface obtains that state and the final level of surface structure all appear to be independent. No one set or individual type of parameter appears to dictate either dynamics or organization alone, reflecting the complexity of the surfaces. In the example of different clast sizes, each of the three clast sizes in the model appears to behave and respond differently. The behaviour of clasts can in part be related to size or edge length, but again no one overriding control is apparent. Slope is more than an accelerator of process action; the differential response of surface clasts to forcing creates a different style of surface dynamics on different slope angles. The behaviour of the model is not always intuitive. This is not to say that the model output is illogical, or has no physical parallel. It is more that the controls on surface behaviour may not always be instinctive. For example, large surface clasts are seen to be the most mobile fraction in a mixed clast size populated surface. The displacement of the more easily movable small clasts is frequently dictated by the larger clasts. Surface structures are commonly jammed around the large clasts, which act as core stones.

The occurrence of surface structure and organization ranging from complete spatial randomness to regularity, linearity and order has been quantitatively shown to be a transition and not a dichotomy of forms. What appears as visually patterned or structured is part of a gradual transition. In the field the observation that surfaces are either patterned and structured or is been demonstrated using the image analysis and also in model the, to be a snapshot of a gradual transition in surface forms. The visual perception is that pattern emerges spontaneously, but quantitatively pattern has been shown to evolve. The form of pattern and structure is complex. Pattern can be described in terms of linearity, clustering, regularity and randomness. Examples of each of these features have been observed in the field and the model output (Chapter 6).

The suggestion of an iterative mechanism of surface modification appears to be supported by the model output (Chapter 6). The evidence from the model shows that when modelled as an iteratively adjusting system, the surface form and behaviour is comparable to features observed in the field. As such the iterative hypothesis of surface modification draws many parallels between the real-world surfaces and the principles of a self-organizing system. The model has shown characteristics of self-organization, such as emergence, convergence and divergence. A consideration of the concepts of self-organization has raised new and interesting ways of thinking about and understanding the behaviour of surfaces.

The nature of spatial change in surface configuration can be used to infer the nature of process action on the surfaces of the north eastern Badia. Rainfall simulation experiments have highlighted the diversity in response to rainfall events across the desert surface which mirrors the variations in surface character measured by the image analysis. The experiments have illustrated the relative rates of runoff generation and hydrological activity between locations, but the absolute rates of process activity and the mechanisms that control the movement and organization of the surfaces remain unknown. Several tentative suggestions can be made as to which are the most important mechanisms behind the movements of surface clasts. All movement mechanisms discussed below are focussed on the promotion of a vertical displacement of the clast which then resettles preferentially downslope.

The most important control on surface processes appears to be the action of water, both through infiltration and overland flow generation. A slope process, controlled by increasing volumes of overland flow downslope, would account for and be coherent with the nature of downslope change in surface character described in this thesis. Overland flow has been assessed at the micro-scale examining only small volumes of runoff generated from a small plot experiment. Volumes of overland flow over the whole slope profile remain unknown given the role of enhanced infiltration around surface clasts, and the variable nature of surface sediments. The surface clasts remain relatively massive when compared to the transport capacity of overland flow and are unlikely to be transported through direct entrainment. Smaller clast fractions may be preferentially sorted downslope by overland flow accounting for some of the evidence presented above. Elsewhere I have undertaken a series of flume experiments examining the influence of scour erosion on clasts in a simulation of conditions on desert slopes such as those seen in the north eastern Badia

(Rosser, 1999). A surprising conclusion of this work was that scour-hole development and erosion on the upslope margin of the surface clast commonly instigated the small scale upslope movement of a clast as it toppled into the hole. Clast movement was greatly inhibited when two or more clasts came into contact and locked, as demonstrated in the cellular model.

The activity of hydrological processes, predominantly infiltration, may result in a differential action of secondary moisture driven mechanisms. Evidence for secondary processes is available in abundance, but again deficiencies of directly monitoring these processes due to their rates and magnitude inhibits our understanding of them in the field. During the winter months severe frosts occur, with notable ice crystal growth around water pipes and standing water pools. The depth of penetration of frost or indeed water infiltration into the desert surface is not known but evidence for the presence of water in the soil horizon is apparent; gyspum and calcrete accretions are all evidence of the presence and transfer of water through the desert soil. Carbonate collar accretions in rocky desert soils have been studied as indicators of water movement through the soil and indicators of previous process activity (McFadden et al., 1999). Their role in directly promoting movement has not been studied. These indicators of water movement may themselves instigate clast movement through for example crystal growth during both calcium carbonate and gypsum accumulation. Of these carbonate appears the most likely to influence the position of surface clasts; gypsum is only commonly found deep in the weathering horizon and not near to the surface, whereas numerous carbonate accretions are often found at the surface or directly beneath surface clasts. Accretions commonly exhibit tapering dripstone spikes, which may promote an iterative vertical movement as they grow. This phenomenon has never been studied.

Material property analysis of the slope sediments indicates a high percentage of clay and previous studies have noted a common occurrence of zeolite (Ibrahim, 1994). Both clay and zeolite are known to swell when saturated with water producing expansive forces, which again may force a vertical unsettling of the surface clasts (Attom and Barakat, 2000). Saturation of sediments may also contribute to a movement of surface clasts through lack of buoyancy of the sediments in the waterlogged sediments, with clasts sinking into the sediments. This has a preferential size sorting, with clasts that are supported entirely in the wetted depth of sediments. On steeper slope angles sediment wetting may also facilitate soil creep and downslope movement of surface sediments.

Additionally thermal properties of the surface need to be considered. The surface clasts are black but the underlying sediments are light brown and it is evident in the field that clasts act as perfect radiators of energy. As such the exposed surface is commonly hot, whereas the underside is frequency cool, frequently sustaining a moist soil patch beneath clasts. This area attracts fauna which may have subsequent impacts on the soil structure. The light sediment surface is highly reflective and observation suggests the penetration of solar energy does not appear to reach a significant depth into the soil profile. This diversity of energy transfer across the surface reflects the differential depths and distribution of wetting during the rainfall simulation experiments. With such a steep wetting gradient and potentially equal temperature gradient, clast movement maybe encouraged by spatial variation in surface cooling or drying.

Mechanisms of movement which have been observed on surfaces described as more conventional desert pavements can be applied to the slopes of the north eastern Badia. One such example is winnowing (Higgitt and Allison, 1998), whereby the surface roughness of the desert develops a rough boundary layer enhancing aeolian sedimentation. Surface clasts iteratively maintain their position at the top of the sediment surface through successive shrink and swell wetting cycles. This was suggested by Higgitt and Allison (1998) for the north eastern Badia, and evidence presented in this thesis supports this; only infrequently are clasts found suspended in an exposed sediment profile, suggesting clasts are either weathered out or maintained at the sediment surface. The rates of this process are however slow. A series of erosion plots in the Badia have been cleared of clasts for a period of 8 years. None of the plots show a significant degree of alteration or reworking from their original state after clearance. Rates of change are either incredibly slow, or formative events are very infrequent. This long term experiment covers a period during which large runoff generating events were known to have occurred (Dotteridge, 1998), suggesting slow rates of geomorphic processes.

A further aspect of this environment that is poorly understood is the role of aeolian processes. Clear evidence has been presented in this thesis which demonstrates the spatial variation of aeolian deposition. The role of sediment remobilisation and deposition in clast burial or exposure still remains poorly understood, but evidence in the field of more intense deposition at slope toes and the scarcity of sediments at the slope crests may equally be explained by aeolian processes as by the slope controlled hydrological processes. The environment is clearly not dominated by aeolian processes. The laminated sediment playa deposits, the spatial variation in clast shape and the step like microtopography all indicate the role of hydrological processes, all of which cannot be attributed to aeolian action.

In addition to the natural geomorphological processes responsible for clast movement, there is a potential role for faunal or anthropogenic induced movement. Herds of goats and sheep frequently walk across the desert in search of fertile grazing land. Visual evidence of clast disturbance through kicking or shuffling by animals and herders has been seen. Animal disturbance may play a critical role, but attributing all of the spatial variations noted in this thesis to this process is dangerous. Animal disturbance does not account for the gradual nature of down slope changes observed in the field, nor the changes in particle shape. The poor relationship between the degree of reorganization of the surface and slope angles, which would directly influence any variation incurred through animal disturbance, is not strong. Anthropogenic disturbance is also either present or not, and would therefore also not show the gradual nature of change identified in the field.

Finally, all of the potential mechanisms of clast movement, both natural and anthropogenic, must be held in the context of the historical conditioning that the north eastern Badia has experienced. As discussed the present environmental conditions may not have been consistent through the development of today's surfaces and as a result nor has the degree of anthropogenic activity been constant. The relative influence and indeed the actual action of all of the processes discussed is not known, but must clearly change through periods of wetter or warmer climate.

In summary, the research in this thesis has generated a series of original findings which contributes to the understanding of coarse clastic surfaces in arid environments, the geomorphology of the northeastern Badia, geomorphological techniques and finally, the application of self-organization to the understanding of clast mantled surface dynamics. There is a need to consider the results of plot based assessments of surface form and process in context of larger scale variations across the landscape. The in situ nature of the surface appears to be the most appropriate perspective from which to study the relationship between surface form and process. Surface clasts have a profound and variable influence on slope hydrology. The surfaces of the northeastern Badia are dynamic and not relict. Subtle links exist between the variability in contemporary surface form and surface process. The processes which act to modify the surfaces are multifaceted, often non-linear and frequently complex. The surfaces exhibit many characteristics of a self-organizing system. The spatial organization of surface clasts is both a cause and effect of variation in slope process action. Finally, no clear evolutionary link between basalt age, slope form and surface character is apparent.

7.3 Extension to previous studies

This study has significantly extended previous work. Advances have been made in methodological approaches, the understanding of coarse clastic slope geomorphology, the understanding of the specific geomorphology of the northeastern Badia and finally, to the application of self-organization as a tool for understanding the dynamics of earth surface systems. The direct comparison of the research presented in this thesis to other studies should be made with caution. Clastic surfaces in arid environments are as diverse in character and genesis as the number of studies which have examined their geomorphology. As a result, many of the findings of previous work are frequently site specific and strongly dictated by the local climate, geology and the evolutionary history of the region in question. Nevertheless several overarching advances can be proposed.

The influence of surface clasts on surface process has been shown to be complex and diverse (Abrahams and Parsons, 1992; Poesen *et al.*, 1994). The influence of clasts can have both a negative and positive influence on process action (Poesen and Ingelmo-Sanchez, 1994). This study has shown a similar variety of influences on surface hydrology in the northeastern Badia. Convergence and divergence in both form and behaviour has been observed to operate in parallel downslope profiles. Multiple regression analysis and the use of a cellular model have demonstrated the sensitivity of surface form and behaviour to slight variations in the character of the clast population. Complex and non-linear behaviour can be related directly to variations in simple characteristics of the surface.

An intimate link between surface form and process has been shown in the northeastern Badia and this research has identified the potential of surface process to alter form, which in turn influences the action of the formative process. Previous work has tentatively suggested a qualitative assessment of the influence of the spatial character of surface form on surface processes (Abrahams and Parsons, 1994; Jean *et al.*, 2000). The tendency for qualitative comparisons is possibly because of the lack of a rigorous direct comparison between two-dimensional patterns (Parsons and Abrahams, 1994; Jean *et al.*, 1999; Tribe and Church, 1999). This study has presented the first attempt to quantitatively demonstrate both the nature of variation and the influence on process of surface clast structures and organization. Much previous work has examined the influence of variable surface form on the action of processes on coarse clastic surfaces (Abrahams and Parsons, 1992). The use of a single storm simulation, specifically formulated to elucidate the differences in surface response as dictated by surface form variations has demonstrated the level of control which surface character affords on surface hydrology.

A direct link between slope angle and particle size is often noted (Bryan, 1925; Rahn 1966; Cooke and Reeves, 1972). The difficulty in drawing direct links between slope and simple clast parameters, as discussed by Vincent and Sadah (1995), has been echoed in the findings of this study. Slope is one of a range of factors that influence slope form and process, all of which are interdependent.

Several studies have focussed on the evolution of clastic arid surfaces and have tried to draw links between surface character and slope profile form and landscape evolution (Allison and Higgitt, 1998; Friend *et al.*, 2000). The ergodic treatment of the results generated in this study indicates a down-slope change in surface form and process action, but extrapolation to an evolutionary link between slope profile form variation and surface character appears tenuous. By implication if, as has been shown, surface form influences slope process then surface form must influence slope evolution. The results from this thesis show a more complex link between surface character, slope form and geology than has been previously suggested (Allison *et al.*, 2001). Whilst the results do not demonstrate an evolutionary change in surface and slope form, they highlight the degree of surface variation within each basalt type, which should be considered within any further study of slope form evolution.

This thesis has provided the first detailed examination of surface hydrology in the northeastern Badia. Kirk (1997) and Warburton (1998) previously conducted work on infiltration and soil surface crusting as a result of rainfall in the region. This research both complements their findings and provides a greater understanding of the processes in action on the undisturbed clast mantled slopes which dominate this region.

Allison *et al.* (2000) summarises a large body of work which has examined the form of the clast mantled surfaces. This thesis has explored the variation of surface form within and between basalts at a greater level of detail than previously undertaken. The findings of this thesis largely complement the previous work published, showing marked systematic variations in surface character with slope form and basalt type. A greater degree of heterogeneity in surface character than that previously noted has been identified in this thesis. The variations observed have been linked directly to local and whole slope controls, in addition to the variable action of processes. The results presented question the evolutionary model of slope form ground surface cover suggested by Allison and Higgitt (1998). This study has demonstrated than a more detailed consideration of within basalt variation as influenced by variable slope form and drainage evolution should be considered within a model of surface form links with slope evolution.

Higgitt and Allison (1999) suggested that a homeostatic modification of the surface form maybe in action in the northeastern Badia. The results of this study qualify this suggestion. Slope hydrology is clearly dictated by the surface form. The results also raise suggestions of the mechanisms and processes directly responsible for the modification of the surfaces. An iterative mechanism of movement appears to be the most likely nature of change to dominate surface form. The actually processes responsible for this type of movement of surface clasts remains a challenging question in the absence of the direct measurement of surface modification processes in the field.

Previous work has developed computer simulations of many geomorphological features and situations based upon the principles of self-organizing systems (Phillips, 1999; Favis-Mortlock *et al.*, 2000; Baas, *in press*). This study uses a cellular automata model to simulate the effects of the interactions between surface clasts. The model demonstrates that self-organizing systems appear to be a valuable tool for increasing the understanding of complex geomorphological phenomena. The common criticism of such a modelling approach is the lack of validation to field evidence (Harrison, 2001). The detailed assessment of surface form variation provided by the image analysis is capable of measuring the surfaces to a precision that can be considered of the same order of magnitude as the variations made to the model parameters which hold a significant influence over modelled surface behaviour. The two methods are therefore complementary.

On its own, the value of the modelling approach would be much less valid (Haff, 1996). Baas (*in press*) suggests that dissatisfaction with theories such as self-organizing arises from their loose and inconsistent interpretation, the lack of a quantitative comparison of model output and direct links to field evidence. This study has attempted to address these concerns. The use of quantitative measures on both the planimetric projection of the surface and the model output allows direct quantitative comparison. Although the model output is not designed to the spatially representative of *real* surface form, the relative variations between locations in the field is considered synonymous with variations generated by the parametric model output.

Many of the relationships previously identified in the northeastern Badia between surface and slope form were limited by their statistical significance, attributed to both the sample size and the spatial extent of the surface area under consideration (Allison *et al.*, 2001). The destructive method of surface characterization previously employed also inhibited the application of the results to an examination of slope process action. The research presented in this thesis has identified significant relationships between surface form and process. Additionally, newly developed measures of surface form, specifically the spatial characteristics of the clast distribution have behaved favourably and often generated significant relationships between form and process where conventional measures do not.

A range of techniques has previously been used to characterize coarse clastic surfaces (Dunkerley, 1995). The image analysis technique developed in this thesis provides a flexible approach that rapidly and precisely measures the in-situ character of clastic surface form. Dunkerley (1995) suggested that the consideration of adequate measures of a clast surface is necessary to provide an appropriate understanding of the formative processes. By using both conventional measures of surfaces character in combination with an in situ assessment of surface form this study has clearly demonstrated the benefits and importance of appropriate measures of surface form. The sampling methodology adopted has identified the significance of considering plot based results in the context of the wider landscape. Without the method adopted the results generated could not have been considered in terms of the whole slope profile or beyond.

Previous attempts have been made to model the modification of coarse clastic surfaces in geomorphology have been made (Ahnert, 1994; Tribe and Church, 1999). Again, the models developed are frequently site specific so direct comparisons between model outputs are difficult. Despite this the modelling approach can produce both logical and sensible results. In doing so it is the first attempt to understand the modification of coarse clastic desert surfaces through an iterative mechanism of adjustment. The model is successful in replicating surface order and structure, as has been observed in the field.

7.4 Recommendations for further research

It is possible to make recommendations for future work based upon the findings of this research.

A more detailed understanding of the links between contemporary surface form and process has been established. The direct processes responsible for the modification of the clasts and whole surface form have deliberately not been addressed in this study. The sporadic and infrequent nature of formative events, which are suggested to be rain storms, inhibits their study within the confines of this thesis. Monitoring of actual clast movement mechanisms, be they instigated by hydraulic deformation of sediment, carbonate accretion, heave processes or ice needle growth, or indeed the direct transport or unsettling of clasts by overland flow, should be undertaken. Additionally, the relative contribution of hydrological and aeolian processes on surface character and process should be studied. Only when these influences are understood can the longer term genesis of these surfaces be approached.

Contemporary surface hydrology has been employed in this study as a surrogate variable for process action within this study. Although not the sole, indeed, direct process responsible for surface modification, hydrology is intimately linked with the transfer of water into the sediment surface. Surface hydrology has been shown to be highly sensitive to variations in ground surface configuration. The results demonstrate that in addition to form directly influencing process action, the influence of process action potentially holds an additional influence on surface form. Direct studies of this type of feedback would be highly beneficial. Surface hydrology potentially holds a significant influence over surface modification. Cyclic heave, carbonate accretion, ice needle action and clay shrink and swell are all intimately linked to slope hydrology. Surface hydrology is therefore a vital clue to understanding surface form and process variations. Previously an evolutionary linkbetween surface form and geology has been made (Allison *et al.*, 2000). The results from this study provide a range of considerations on scale, surface form and process variability and adequacy which provide a template for future studies into the evolution of coarse clastic slopes in arid environments.

This study has been conducted principally in a relatively small area on the surfaces of one basalt type. In order to gain a more comprehensive understanding of the evolutionary link between slope form and ground surface configuration, suggested by Allison and Higgitt (1998), similar studies should be undertaken on additional basalt surfaces. During the research for this thesis several attempts were made to gain an understanding of the three-dimensional form of the surfaces, combining both the planimetric view of the surface with an assessment of the vertical extent of surface clasts. A three-dimensional assessment of surface form would combine the benefits of the planimetric projection with a consideration of the attributes of the surface which a measure of surface roughness, which influences flow depths and routing. Digital photogrammetry using stereo imagery to produce a three-dimensional representation of the surface form was attempted in this study. The error incurred from the additional complexities of measurement in three dimensions drastically reduces the feasible size of sample obtainable using this technique. A more sophisticated method of image capture and analysis may yield more success. DGPS was employed to conduct highly detailed and accurate (± 0.02 m) cross profile transects of the clast surface, similar to the approach used by Dunne *et al.* (1992) who assessed the downslope increase in fractal dimension of surface roughness. This approach may provide additional clues as to the dominant controls on surface form and process.

Previous work has demonstrated the importance of the underlying sediments on clast mantled desert surfaces in controlling surface hydrology and desert pavement evolution (Wells *et al.*, 1995; Brown and Dunkerley, 1996; MacFadden *et al.*, 1998). This study has primarily focussed on the influence of clast form and surface configuration in controlling surface hydrology and development. Data from the northeastern Badia suggest that the downslope distribution of sediments is effectively homogeneous, but no study of soil structure, material properties or the presence of vesicular horizons has been made. Even though particle size variations and the mineral composition of the sediments is constant downslope, the presence of surface sealing and crusting, the variable depth of sediments and the variable degree of clast burial should all be taken into account, even though these features are not reflected in the variations in material properties measured.

The model of surface modification and spatial organization can be developed further which would be of direct benefit to the understanding of surface geomorphology. First, currently the spatial arrangement of the starting conditions of the model is randomly generated, and in therefore not a direct simulation of the naturally occurring surfaces. Second, the particle size distribution and clast shape based on a cellular grid is a very crude representation of reality. Ideally, a method which extracts both particle size characteristics and clast arrangements directly from the images of the in-situ surface would be undertaken. The stability and evolution of real surfaces could then be undertaken. Ideally the model would also be temporally constrained, through for example surface dating, such that the timescales and rate of change could be suggested. The model is also currently incapable of simulating weathering of clasts which alter clast form. If the spatial variations in clast form, for example clast rounding and texture are synonymous with a temporal modification of surface form, then the alteration of clast form during the iterations of the model would be beneficial.

Many of the methods developed in this study can be applied to other geomorphological situations. The method of slope profile location combines a long established method of profile location with a new computer based profile extraction procedure. The aerial image capture procedure operates at a scale which is of particular relevance to the study of landforms and generates detail in excess of that of conventional aerial photography over a wider spatial extent than ground based photography. The automated image analysis developed for particle characterization could also be applied to similar coarse clastic surfaces, for example gravel-bed rivers or periglacial surfaces. The use of rain storm simulation experiments as a way of forcing differences in surface process to become apparent could again be applied to other landscape where variability in surface process is only very subtle. Finally, the modelling approach has demonstrated an ability to generate alternative ways of thinking about landforms, through concepts such as self-organization.

This thesis is part of ongoing research in arid zone geomorphology, the behaviour of earth surface systems and the specific context of the northeastern Jordanian Badia. The results raise questions which may help to define the future research direction in all of these areas.

'Stones have been known to move'

Shakespeare, Macbeth, III, iv

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